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THE THEORY OF UNDERDRAINAGE

By
W. J. SCHLICK

BULLETIN 50
ENGINEERING EXPERIMENT STATION

Ames, Iowa

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917. Authorized September 23, 1918.

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THE purpose of the Engineering Experiment Station is to afford a service, through scientific investigations, evolution of new devices and methods, educational technical information, and tests and analyses of materials:

For the manufacturing and other engineering industries of Iowa;

For the industries related to agriculture in the solution of their engineering problems;

For all people of the State in the solution of the engineering problems of urban and rural life.

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The Theory of Underdrainage

I. INTRODUCTION.

1. **Importance of Underdrainage in Iowa.** There has probably been no single factor, in the agricultural and commercial development of Iowa, of greater importance than drainage, and particularly underdrainage. It has been estimated on good authority that the lands in Iowa needing drainage include at least 7,100,000[1] acres, and that this work will cost $400,000,000[2], a sum equal to the cost of the Panama Canal. Practically all of this 7,100,000 acres will require underdrainage to put it in the condition for maximum crop production.

It seems from the best available estimates that not much over 50 per cent of the ultimate drainage work in Iowa has been completed. One Governor of Iowa, in his inaugural address, estimated that up to 1911, 125,000[3] miles of underdrains had been constructed in Iowa, at a probable cost of $105,000,000. Up to the same year, the drainage work in one Iowa County, Winnebago, was estimated to have cost $1,700,000[4]. Late in 1918 it was stated that when work then in course of construction was completed, Kossuth County would have expended more than $7,000,000 for drainage improvements.

While these figures are only estimates, they are as reliable as any which are available, and they serve to show the vast importance of drainage work, and particularly of underdrainage work, in this state. It is probable that during the next decade at least two hundred millions of dollars will be required for drainage work in Iowa, and that the major portion of this will be expended for underdrainage systems.

2. **Early History of Underdrainage.** One of the earliest records of underdrainage is found in the writings of the Roman, Columnela, who lived in the first century of the Christian Era. The Drainage Journal, Vol. XXIV, gives the following translation from that writer's works*: "We know of two kinds of ditches, those which are wide open and those which are hidden.. For hidden ditches one will dig trenches three feet deep, which shall be filled with pebbles or pure gravel, and then the whole will be filled with earth taken from the trench." That the Roman peoples did not, however, fully realize the need for drainage, or its benefits, is shown by the existence of the noted Pontine Marshes at the time of the fall of the Roman Empire.

In the middle of the seventeenth century, Walter Blith of England, in writing on drainage, said that drains to be efficient must be laid

[1]Proceedings, Iowa State Drainage Association, 1912.
[2]Proceedings, Iowa State Drainage Association, 1912.
[3]Proceedings, Iowa State Drainage Association, 1911.
[4]Proceedings, Iowa State Drainage Association, 1910.
*Geo. M. Thompson, Proceedings, Iowa State Drainage Association, 1911.

three or four feet deep. In these writings he recommended the use of trenches filled with fagots or stones. A little later, about 1730, James Smith of Deanston, Scotland, and Joseph Parks, Engineer for the Royal Agricultural Society of England, made numerous experiments which gave drainage development an added impetus. The Encyclopedia Brittanica in speaking of Smith and his work states that "—he insisted on the necessity of providing each field which needed draining at all with a system of underground channels..and so near together that the whole rain at any time on the surface should sink down and be carried off by the drains." Smith believed that the distance between drains should be regulated by the retentiveness of the soil, but recommended parallel drains, 10 to 40 feet apart and 30 inches deep. In his earlier works, he recommended trenches filled with 12 inches of stones which would pass a three inch ring. In his later work he advised the use of burned clay tile, or "field pottery," in the shape of a letter U inverted and generally used without the bottom plate, or "sole," which was commonly used later. At about the same time Parks advocated drains further apart and at a depth of at least four feet. Both of these men were strong advocates of underdrainage, but they encountered and held different opinions upon one of the problems still confronting us today; namely: the determination of the most advantageous spacing and depth for lateral drains.

The earliest tile drainage in the United States was probably that of John Johnson of New York. While on his way to the coast to leave Scotland, Mr. Johnson saw some tile being burned, and on making inquiry was so impressed with the idea that he brought some of the tile to this country with him. He laid his first tile in 1835. The results were so gratifying that he continued the work till in 1851 he had 16 miles of tile drains. In the meantime, he imported a tile moulding machine, after which tile could be obtained at a price, which as he expressed it, left the farmer no excuse for wet land. It seems probable that Mr. Johnson laid his tile lines very close together and it is known that he used very small tile (not to exceed two inches in diameter) with collars.

With the westward emigration from the New England States to Ohio and Indiana, and later from there to Iowa and Illinois, came the practice of tiling the wet lands of the fertile Mississippi Valley. There has been a constant and rapid progress in this work during the last quarter of a century till now these two states, and particularly Iowa, have taken the lead in underdrainage development. The knowledge of the forms and movements of soil moisture, or groundwater, and their relationships to underdrainage and to crop production has increased greatly, and the engineering features of underdrainage design have been made more accurate through investigations which have developed new methods and formulas, or shown how to use old ones more correctly.

3. **Purpose of this Bulletin.** The general knowledge of the relationships between soil characteristics, the forms and movements of soil moisture, underdrainage and crop production is so small that many engineers and landowners either consider these factors as almost wholly unrelated or do not consider the possibility of an interrelationship at all. In reality these factors, in so far as they are of especial significance in underdrainage work, are all closely inter-related and inter-dependent.

Some readers may feel at first that much of the material presented in this bulletin is an encroachment on the sphere of the agriculturist, but such is not the case. The underdrainage systems of Iowa are constructed primarily in agricultural lands to increase the potential production of those lands. The study of soils and soil moisture and their relation to crop production is essentially agricultural, but the relation of these to drainage is a part of drainage engineering and a knowledge of them is essential to the engineer employed in underdrainage work.

The question of the most advantageous spacing and depth for underdrains, regarding which James Smith and Joseph Parks held different views nearly a century ago, is not debated so much now as it is ignored by landowners and engineers who unthinkingly follow some precedent or local custom. The question of the proper rate of runoff is treated in much the same manner and is usually decided upon as an independent feature of the design, and this decision altered to meet the landowner's ideas as to the amount he thinks his drainage system should cost. The proper spacing and depth for lateral underdrains are dependent upon the amount of the surplus soil moisture and the rate of its movement through the soil. These in turn are dependent quite largely, in each locality, upon the character of the soil. The same principles which determine the proper spacing and depth for the lateral underdrains also determine the rate of runoff from these drains, and a correct understanding of these principles is dependent upon a general knowledge of soils and soil moisture.

It is the purpose of this bulletin to present those principles which determine the efficiency of the operation of a well-constructed underdrainage system. Only those phases of the whole study of soils and soil moisture that are essentially a part of drainage engineering are discussed, and these are treated from a drainage standpoint. It is not intended that any part of this bulletin be taken as a discussion of these principles from a strictly agricultural standpoint.

Some additional matter of a more strictly drainage engineering nature has been included so as to make a more complete presentation of the principles governing the design of underdrainage systems.

It is hoped that these discussions will be of value both to the engineer and to the landowner and that they will lead to a more general and correct understanding of the principles of the intelligent design of underdrainage systems.

4. **Acknowledgements.** Much of the material in this bulletin, particularly those chapters relating to soils and the forms and movements of soil moisture, is a compilation of material gathered from other sources. These subjects and their relation to crop production come, primarily, in the field of the agriculturist; the discussions of these points are taken principally from agricultural text books. The only claim for originality in this connection is in the presentation of the whole subject from a drainage standpoint.

The suggestions and criticisms offered by Mr. A. Marston, formerly Dean and Director of the Division of Engineering, Mr. W. H. Stevenson, Professor of Agronomy and Mr. S. W. Beyer, Dean and Director of Engineering, all of the Iowa State College, have been of much value in preparing and arranging the subject matter presented. Acknowledgement is also made of the valuable assistance given by Professor Stevenson and Mr. R. E. Smith, Associate Professor of Soils, in reviewing those chapters relating to soils and soil moisture.

II. SOILS.

A clear understanding of the nature and movements of soil water as related to both agriculture and drainage requires some knowledge of the various kinds of soils and of their physical or mechanical composition. Such elementary phases of the subject as are thought necessary for a comprehensive study of the succeeding discussions will be presented here.

5. **Soil Areas of Iowa.** The typical soil areas of Iowa might be listed as follows:

(1) Wisconsin Drift.
(2) Iowan Drift.
(3) Southern Iowa Loess and Kansan Drift.
(4) and (5) Missouri and Mississippi Loess.
(6) Moraines.
(7) Gumbo.
(8) Bottom Lands or Alluvium.
(9) Peat.

Each of these different soil areas has its peculiar properties and each presents a different problem in drainage due, primarily, to differences in topography and the physical or mechanical composition of the soil. The map (Fig. 1) showing the location of the six larger areas and the description of each area are taken in most part from published reports of the Iowa Agricultural Experiment Station. The data as to the peat areas are taken from the published report of investigations by the State Geological Survey.

(1) *Wisconsin Drift Area.* The soil of this area is the till deposited by the Wisconsin Glacier, the last of the great Keewatin ice-sheets to invade Iowa. This drift area includes all or part of 30 counties in

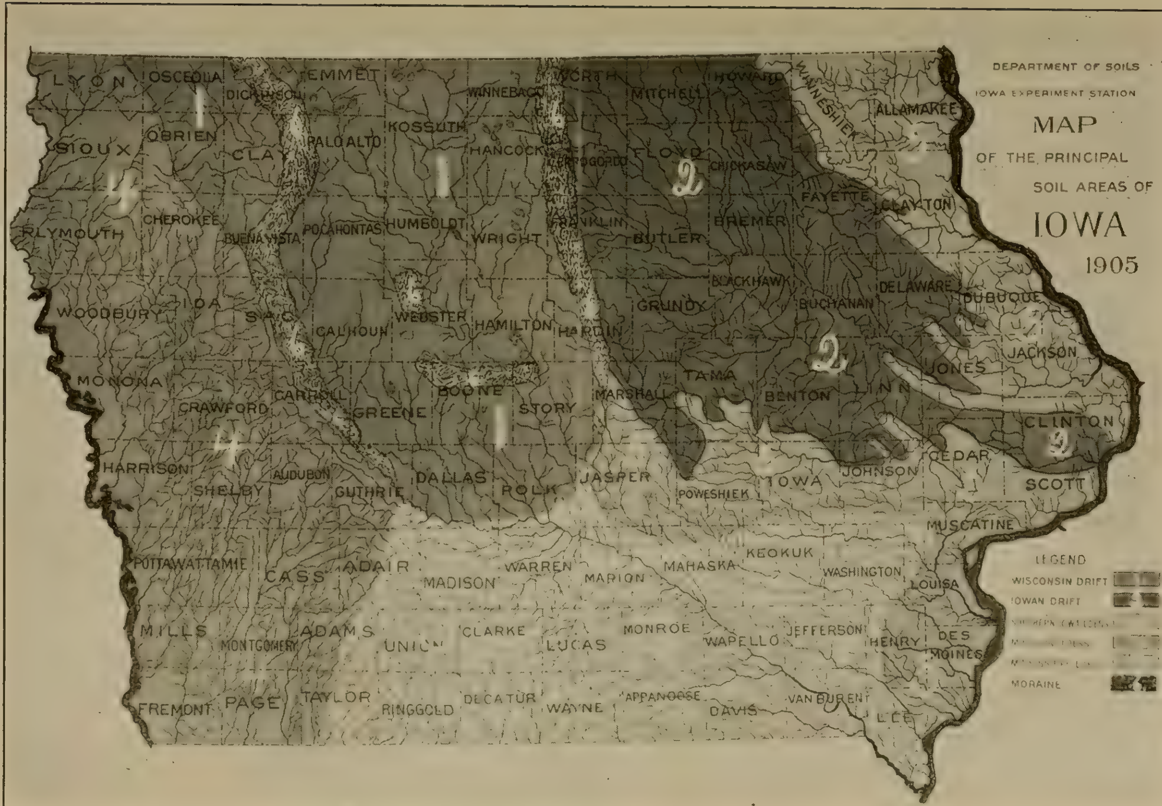

Fig. 1. Principal Soil Areas of Iowa.

the western portion of the north-central part of the state. This area, geologically speaking, is very new and its natural drainage very incomplete. A few large streams, notably the Des Moines River and its large tributaries, cross it but have not had time to extend their tributaries very far back from the main streams. Nearly the whole area is a wide prairie with numerous sloughs and ponds, except for the eastern and western edges where stretches of low hills, the remains of terminal moraines, occur.

The soil of practically all of this area is a black loam top soil, sometimes of a sandy or clayey nature, with a yellow clay or sandy yellow clay subsoil. A few small areas of partially decayed peat are found in the swales and sloughs. Owing to the newness of this drift the rocks are only partially decomposed causing the formation of light alkali spots around the edges of a few ponds and sloughs which have surface drainage but not adequate underdrainage. Nearly all of this area requires, and much of it now has, artificial drainage, both by underdrains and open ditches. Thorough underdrainage has been found to be a very efficient remedy for the alkali trouble.

(2) *Iowan Drift Area.* The Iowan Ice-sheet invaded Iowa at an earlier period than the Wisconsin, and extended considerably further east, so that the Iowan Drift Area now exposed covers an area just east of soil area No. 1. The Iowan Drift Area comprises all or part of 29 Counties. This area is nearer maturity than the Wisconsin Drift Area and has more complete natural drainage, as is evidenced by the absence of ponds and sloughs, and by the deeper and more pronounced natural water courses.

The soil of the Iowan Drift area is much the same as that of the Wisconsin. The top soil is generally a black loam, sometimes sandy or gravelly, while the underlying strata are sand, sandy clay or clay. Some sections of this area have a substratum of sand or gravel at a depth of four to six feet which often is a great aid to underdrainage, though this layer is quite often overlain with a layer of clay or sandy clay 6 inches to 18 inches in thickness. Practically no peat and but very few "alkali spots" are found in this area.

(3) *Southern Iowa Loess and Kansas Drift Area.* This area is shown in Fig 1 as the Southern Iowa Loess Area, and includes practically all of the state south of the Wisconsin and Iowan Drift Areas, between the Missouri and Mississippi Loess Areas. The subsoil formation is of the till from the great Kansan Ice-sheet which covered Iowa long before either of the other ice-sheets mentioned. At a later time the deposit known as the Iowa Loess was placed over this deposit of till. This area is much older than either of the other drift areas and has numerous well defined natural drainage channels, though many nearly flat areas of both bottom land and upland now exist.

The top soil of this area is the loess deposit and may be described as a fine black loam. It is usually found now only on the divides,

erosion having removed it from the hillsides. Where found upon the fairly level divides it usually has a depth of about two feet. The subsoil is the till from the Kansan Glacier, and upon the badly eroded portions this former subsoil is now the top soil. This till is a very close clay, usually yellowish red to red brown in color. It is so impervious as to have given the name "Hardpan Area" to much of this section. Neither the loess nor the till underdrain as readily as the soils in other portions of the state, though the efficiency of the underdrainage systems increase with the length of service.

(4) and (5) *Missouri and Mississippi Loess Areas.* These two areas are similar so far as the characteristics of interest in this discussion are concerned, and hence are classed together. The location and extent of these areas are shown by Fig. 1. These areas contain many examples of the two topographical features characteristic of deep loess deposits; namely, the well-rounded convex curves of the slopes and ridges, and the vertical escarpments. Although this soil erodes easily, it still has the property of standing nearly vertical in cuts, either natural or artificial, as is evidenced by the steep bluffs along the Missouri River.

The soil of these loess areas is rather porous and loose. It often allows of such rapid aeration that the humus is decayed so rapidly that the desired amount cannot be accumulated. From an agricultural standpoint, this area is marked by infertile tracts often of as much as 50 acres, the infertility being accredited to the loss of the surface layer of soil. The loess is not unusually as much as 100 feet deep, so that it can be readily underdrained.

(6) *Moraines.* The areas of morainal drift now exposed in Iowa lie in narrow belts on the eastern and western edges of the Wisconsin Drift Area and two small areas within this drift area. These areas were formed principally at the extremities of the ice-sheet and in consequence have better developed systems of natural drainage channels and a correspondingly smaller need for underdraining.

The soil of these morainal areas is very similar to that in the adjoining drift areas, except that it contains a larger percentage of coarse material and more boulders.

From the standpoint of underdrainage these morainal areas are comparatively unimportant. Because of the development of the natural drainage systems only those areas of bottom land along the streams are wet enough to need underdrainage.

(7) *Gumbo Areas.* The Gumbo areas of Iowa are a very small portion of the whole state and are found in only two localities. A narrow strip from two to five miles wide, extends from the center of Woodbury County to the center of Pottawattamie County, parallel to the Missouri River and about seven miles east of it. In Washington, Muscatine, Henry, Des Moines, Van Buren and Lee Counties are sev-

eral irregular but small areas. Gumbo is found in both upland and lowland areas, and is practically the same, from a drainage standpoint, wherever found.

The soil of these gumbo areas is very fine grained and waxy, and is usually black in color. The lowland gumbo is usually finer grained than that of the uplands, though the latter is often just as sticky and waxy as the former.

Strange as it may seem, this soil seems to drain more readily than the black loam soils of other areas. Reports show that underdrains placed as much as 200 feet apart have given satisfactory results, and where ever underdrains have been laid in Iowa gumbo, there is reported to be little doubt that lateral drains 100 to 150 feet wide will give satisfactory results.

8. *Bottom Lands or Alluvium.* These terms are applied to the soil formations in the present and former flood plains of streams. Owing to the mode of formation the characteristics of these soils vary greatly. The top soil is usually a fine black loam; the subsoil may be anything from a very close clay to a coarse gravel, though each of the separate layers is usually of fairly uniform composition and fairly distinct.

If the subsoil is of close clay, as often occurs, this soil is more difficult to drain than any of the other types of Iowa soil, unless it be those sections of Southern Iowa where the close clay of the Kansan Drift is at or near the surface. It can be successfully underdrained, however, if the proper spacing and depth of drains be used.

(9) *Peat.* The peat areas of Iowa may be divided roughly into two classes; the thick deposits found in the morainal belt along the eastern side of the Wisconsin lobe, and the shallow beds in the counties to the west.

The peat beds in the morainal belt vary in thickness, when wet, from three or four feet to twenty or thirty feet and occasionally more. The peat in the shallow deposits further west is rarely over three feet thick, even when wet. The subsoil of the peat areas is almost universally a marly clay.

The Report of the Iowa Geological Survey, Vol. XVII, gives the areas of the peat beds of Iowa, by Counties, as follows:

Clay - -	Trace	Palo Alto - -	Trace
Dickinson - -	50 acres	Webster - -	800 acres
Emmet - -	400 acres	Winnebago - -	4055 acres
Hamilton - -	Trace	Wright - -	800 acres
Hancock - -	375 acres	Worth - -	1540 acres
Kossuth - -	625 acres	Cerro Gordo - -	1610 acres
Franklin - -	590 acres		

Owing to the impurities in these peats they are generally available for agricultural uses within two or three years after they are

thoroughly drained. Tile drainage is not a difficult matter wherever it is possible to place the tile in or upon the subsoil. The instability of the wet peat, and its great shrinkage upon drying make underdrainage of the deeper peat beds uncertain because of construction and maintenance difficulties.

6. **Mechanical Composition of Soils.** *Viewpoints of the Drainage Engineer and the Agriculturist*: The agriculturist in considering the physical properties of the soil of any region will divide his information into that relating to the top soil, or the seed-bed of cultivatable crops, and that relating to the subsoil. The drainage engineer may or may not divide the soil in this way depending upon the thickness of the top layer of soil. If this surface layer is four or five feet thick the lower stratum will have little effect upon the underdrainage unless its perviousness or imperviousness be extreme. The drainage engineer will look rather upon the soil as a whole, and base his conclusions upon its general physical properties, considering of course any unusual formations. In some cases he may need to consider more than two layers or strata. The drainage engineer should not ignore the study of the agricultural possibilities of the soil in any proposed drainage district because upon this will usually depend the feasibility, from an economic standpoint, of the proposed work.

Texture and Structure: The physical character of a soil is usually expressed by the terms *texture* and *structure*. The term *texture* is used to refer to the size, or range in sizes, of the individual soil grains, while the term *structure* refers to the arrangement of these particles.

7. **Soil Texture.** *Soil Separates:* The various classes of soils, ordinarily designated as clay, loam, sandy clay, etc., derive their physical characteristics and textural classes and groups from the size of the individual grains of which each is composed. The size of grain which places a soil in one of these classes is chosen arbitrarily, though those adopted by the United States Bureau of Soils are usually taken as a standard. The soil whose grains, as determined by analyses, are all between the upper and lower limits of size set for one class, is termed a soil separate. The list of the soil separates and the limits of sizes of grains for each as adopted by the Bureau of Soils are given in Table 1.

TABLE I. SOIL SEPARATES.

Separate	Diameter of Grains, Millimeters
Fine gravel	2.0 - 1.0
Coarse sand	1.0 - 0.5
Medium sand	0.5 - 0.25
Fine sand	0.25 - 0.10
Very fine sand	0.10 - 0.05
Silt	0.05 - 0.005
Clay	0.005 - 0.00

(1 milimeter = 0.03937 inch.)

Soil Separates in Common Soils: These soils separates must not be confused with the ordinary soil groups, (clay, loam, sandy loam, etc.) even though the names are similar. Each of the various soils, as

popularly designated, is made up of varying percentages of the soil separates given in Table I. Tables II and III show the percentages of the various separates present in some of the common soils together with some of their physical properties. All the data in Table III, except the per cents of pore space and the numbers of soil grains per gram, are the results of analyses of samples of these soils.

TABLE II.

PHYSICAL COMPOSITION OF COMMON SOILS.

	1 Fine Gravel	2 Coarse Sand	3 Medium Sand	4 Fine Sand	5 Very Fine Sand	6 Silt	7 Clay
Coarse Sand	More than 25% (1 + 2)					0-15%	0-10%
	More than 50% (1 + 2 + 3)					Less than 20% (6 + 7)	
Medium Sand	Less than 20% (1 + 2)					0-15%	0-10%
	More than 20% (1 + 2 + 3)					Less than 20% (6 + 7)	
Fine Sand	Less than 20% (1 + 2 + 3)					0-15%	0-10%
						Less than 20% (6 + 7)	
Sandy Loam	More than 20% (1 + 2 + 3)					10-35%	5-15%
						More than 20% and less than 50% (6 + 7)	
Fine Sandy Loam	Less than 20% (1 + 2 + 3)					10-35%	5-15%
						More than 20% and less than 50% (6 + 7)	
Loam							15-25%
						Less than 55%	
						More than 50% (6 + 7)	
Silt Loam						More than 55%	Less than 25%
Clay Loam						25-55%	25-35%
						More than 60% (6 + 7)	
Sandy Clay						Less than 25%	More than 20%
						Less than 60% (6 + 7)	
Silt Clay						More than 55%	25%-35%
Clay							More than 35%
						More than 60% (6 + 7)	

Taken from "Principles of Soil Management," Lyon and Fippin.

TABLE III.

PHYSICAL COMPOSITION OF COMMON SOILS.

Soils—	Per cent of Separate Present — Fine gravel	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay	Pore Space	Number of Grains in 1 gram, millions	Surface Area of 1 Cu. Ft., sq. ft.
Coarse Sand	5.0	13.0	27.0	30.0	11.0	8.5	5.5	40.0	3,276	40,500
Medium Sand	5.0	13.0	20.0	32.5	14.0	9.0	6.5	41.8	3,956	44,500
Sandy Loam	5.0	10.0	11.0	26.0	11.0	22.0	15.0	51.0	6,485	66,600
Fine Sandy Loam	2.0	2.5	5.0	20.0	27.5	32.0	11.0	50.0	4,902	62,000
Silt Loam	1.0	1.5	2.5	6.0	11.0	56.0	22.0	53.0	9,639	104,000
Clay Loam	3.0	5.0	5.0	12.0	10.0	28.0	37.0	54.0	16,371	136,000
Clay	0.0	2.0	2.5	5.5	7.0	37.0	46.0	56.0	19,525	142,000

(Compiled from data given in "Principles of Soil Management," Lyon & Fippin.)

Soil Separates and Crop Adaptation: Figure 2 shows the crop adaptation and composition of some soils whose analysis gave the data from which the curves were plotted. By watching the yields of various crops and noting the general characteristics of any soil and then referring to these curves it should be possible to determine something of its physical composition.

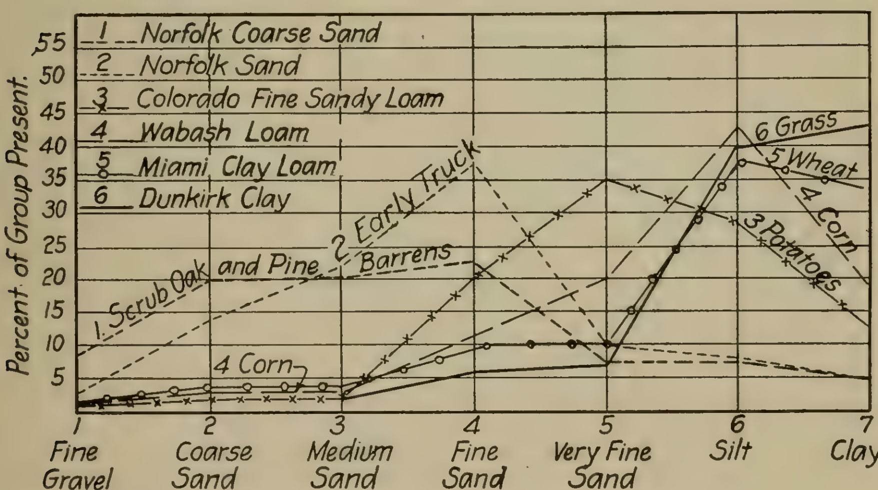

Fig. 2. Crop Adaptation and Composition of Some Soils.

However, it should be borne in mind that these data, both as to physical composition of the soil and the crop to which it is best adapted, refer more particularly to the seed bed or surface layer than to the total depth that must be considered in connection with underdrainage.

Size of Soil Grains: The sizes of the individual particles which compose any natural soil vary greatly. For example, the sandy loam listed in Table II has particles of fine gravel, which may vary in size from

2.0 m.m. to 1.0 m.m. and the clay, whose particles are less than 0.005 m.m. in diameter. If the largest limit be taken for the clay particles, it would require 5050 of them to span one linear inch. The variation in sizes of the grains composing all soils is not as great as that just referred to, though the variation is great for all natural soils.

Effective Diameter: All formulas for the movement of water through the soil take into account either directly or indirectly, the size of the grains composing the soil in question. Where the size of grains is used directly it is expressed as the "effective diameter" or the "effective size." This is a diameter such that if grains of this diameter were substituted for the soil in question the porosity would remain the same. The effective diameter is also defined as the diameter of the grain which has 10% of the grains smaller than itself and 90% larger. In other words, the effective diameter or effective size of grain in any soil, however determined or defined, is a size such that if grains of this size were substituted for the soil in question a soil of the same hydraulic properties, as far as the movement of ground-water is concerned, would be produced.

Uniformity Coefficient: In his formula for the movement of water through filter sands, Mr. Allen Hazen introduces a factor known as the "Uniformity Coefficient" in order to give expression to the variety of sizes of the grains of any sample. To determine this coefficient, first find the size of grains such that 60% of the material is of smaller grains and 40% of larger grains. This result divided by the effective diameter of grain for the entire sample gives the uniformity coefficient. In his determination on filter sands, Mr. Hazen made a sieve analysis, and then plotted a curve using the diameter of grains as absessae and the per cent by weight passing through the various sieves as ordinates. From this curve it was easily possible to locate the effective size of grain and the size which divided by the effective size would give the uniformity coefficient.

It is doubtful if, with the present methods of determining the size of soil grains, it would be possible to apply this method to natural field soils. The grains in natural soils are too small to permit of successful sieve analysis so that it is probable that the best method of determining the effective size and uniformity coefficient would be to determine the per cents of the various soil separates present and then compute the value of the effective size and the uniformity coefficient. Such a result would be only approximate at best and for calculating soil water movement would probably not be desirable.

In his book on Soil Physics, Professor King gives the data in Table IV for samples of the various soils. It will be noticed that there is a little apparent variation in the data in this table and that in Table III, but this is probably due to slight differences in the samples of the various soils analyzed.

TABLE IV.

PROPERTIES OF COMMON SOILS.

Kind of Soil.	Effective Size of Soil Grains, M. M.	Per Cent of Pore Space	Surface Area of 1 Cu. ft. of Soil Grains, sq. ft.
Finest Clay Soil	.004956	52.94	173,300
Fine Clay Soil	.008612	48.00	110,500
Heavy Red Clay Soil	.01111	44.15	91,960
Loamy Clay	.02542	49.19	70,500
Clayey Loam	.01810	47.10	53,490
Loam	.02197	44.15	46,510
Sandy Loam	.03035	38.83	36,880
Sandy Soil	.07555	34.45	15,870
Coarse Sandy Soil	.1432	34.91	8,381

Number of Soil Grains: The number of grains in a sample of soil may be readily computed when the mean diameter of the grains and the specific gravity of the soil particles are known. The value of 2.65 for the latter is fairly constant for the soil particles, but it is not correct for a volume of the soil. The data as to the numbers of soil grains in 1 gram of soil given in Table III were computed in this way from data obtained from an analysis of each sample.

Surface Area of Soil Grains: The surface area of the particles composing a given weight of a soil may be computed from the number of particles and their mean diameter, each particle being taken as a true sphere. The relation of the fineness and number of particles to the surface area is well illustrated by the data in Tables III and IV. The finer the grains the greater is the number of particles and the total surface area of particles. This fact has a very important bearing on the capacity for, and movement of, capillary moisture.

8. **Soil Structure**. The term structure is used to refer to the arrangement or grouping of the soil particles. Upon the structure depends, to a large extent, the per cent of pore space and the size and number of pores. This effect will be treated more fully under a discussion of porosity.

In any soil in natural condition, especially the top or cultivated layer, the individual particles are found not as simple grains but as groups of grains or granules. If these grains be arranged very compactly in the granules the effect is to produce a soil which has the same properties in regard to the movement of water and air as a larger grained soil. Arrangement No. 4 of Fig. 3 is an illustration of the effect of such a grouping into granules. Some soils have varying sized grains which become mixed as do the particles in a well mixed concrete. The smaller particles fill the spaces between the larger ones so completely as to make it a nearly compact mass. When many of the fine-grained soils are subjected to long continual saturation by standing water, the finer particles move downward till they lodge in the soil pores. This action produces a very compact layer which is often termed "hard pan." When a soil, which is composed of grains of properly graded sizes, is worked while wet, as by the tramping of

stock, the smaller particles are carried into the spaces between the larger grains. This produces a condition commonly known as "puddled."

9. **Porosity.** *Porosity and Size of Soil Grains:* The relation of the soil grains to the percentage of pore space is well shown by the data in Tables III and IV. The clay soils having the smallest sized grains have the largest per cent of pore space, while the sands and gravels having the larger sized grains have small per cents of pore space. This

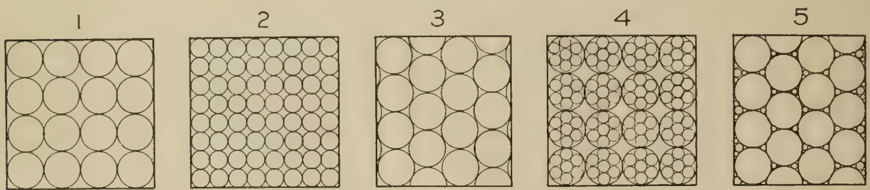

Fig. 3. Ideal Arrangement of Spherical Soil Particles.

(1) and (2), columnar order, 47.64% of pore space; (3) oblique order, 25.95% of pore space; (4), compound spheres in oblique order, 74.05% of pore space; (5), three sizes of spheres with closest packing, about 5% of pore space.

may lead to the question of why the sandy soils appear to be more porous than the clays. It is well known that a sandy soil will drain out much more readily than a close fine-grained clay soil. This apparent contradiction is due to the fact that pore space in the clay soil is divided up into such minute channels that water or air passes through them with difficulty, while in the sandy soil with its smaller amount of pore space the pores or channels are much larger and afford a much freer passage for either air or water. The effect of the amount of pore space and size of pores will be discussed more fully in the following chapters.

Porosity and Structure: The porosity of any soil depends not only upon the size but also upon arrangement of the individual particles. The principle is well illustrated by the data in Tables III and IV and by Fig. 3 which shows the effects of arrangement if all particles be considered as spheres. Arrangements 1 and 2, Fig. 3, have the same per cent of pore space but in the first arrangement there are only 16 pores while in the latter there are 64. The spheres in these two cases have diameters of 1 and ½ respectively. If the diameter be again reduced so that it is ¼ the per cent and total amount of pore space remains the same but the number of pores is increased to 256. The effect of this reduction upon the movement of soil water or soil air is readily seen as in the first case it is divided into only 16 streams while in the second case it is divided into 64 streams, each proportionately smaller than those of the first arrangement. If the particles be arranged in the oblique order shown as Arrangement 3, the pore

space is reduced to a minimum for spheres of uniform size. But if the structure be that shown in Arrangement 5, the pore space is further reduced because the smaller particles continually fill the spaces between the larger ones. The effect of the grouping into granules is shown in Arrangement 4, which gives the largest per cent of pore space of any of the arrangements shown.

Figure 3 must not be taken as illustrating the arrangements of particles in any natural soils. These diagrams are only given to show the effects of different arrangements upon the total pore space and the size of pores. The particles in any natural soil would not conform to any of these arrangements but would be modifications and combinations of all or of several of them.

10. **Porosity and Perviousness.** Because of a misunderstanding of their true meaning, these two terms are often used as synonyms. These terms are neither synonyms nor antinyms, though they are more nearly antinyms than synonyms; in a number of soil samples the most porous, the soil with the highest per cent of porosity, is normally the least pervious.

The porosity of a soil depends upon the total amount of pore space, and has no reference to the size or hydraulic efficiency of the channels formed by these pore spaces. The perviousness, or permeability, of a soil depends upon the readiness with which liquids or gasses (usually water or air) will pass through the soil. This depends upon both the size and the hydraulic efficiency of the channels formed by connected pores. Normally, the soil with the smallest individual grains has the highest per cent of pore space. In such soils, as very fine grained clay soils, the soil pores are so small and are so disconnected that the soil is practically impervious. On the other hand, the coarser grained soils, as sand or granular loam soils, have a much smaller per cent of pore space, but the pores are larger and form such efficient hydraulic channels (comparatively) that soil air and soil water pass through them rapidly.

In loam soils, porosity is determined largely by the soil texture and the permeability by the soil structure; the porosity normally decreases as the permeability increases or vice versa.

III. SOIL MOISTURE.

In discussing soil moisture and its movement only such phases of the subject as have an especial relation to underdrainage will be considered. The subject in its entirety is so complex that only an elementary treatment is either possible or desirable here.

11. **Source of Soil Moisture:** Of the water which falls to the earth's surface as rainfall, one portion runs away over the surface to the natural drainage channels, another portion seeps into the ground, and the third portion evaporates from the place where it falls. It is

this second portion, that which is taken up by the soil, which is of particular interest in this discussion.

12. **Moisture Content of Soils:** The capacities of soils to take up and hold moisture vary greatly with the different soil types and formations. The soils with the larger percentages of porosity hold the larger amounts of moisture. The moisture content is usually expressed as a percentage of either the dry weight or of the volume of soil, or as a depth in inches, which is simply a modified way of expressing it as a percentage of the volume. Table V shows the variation of the moisture capacity of a soil with the fineness of the soil grains. The maximum and minimum moisture content each increases as the size of the soil grains decreases. Any treatment, such as underdrainage, as will tend to increase the moisture capacity of a soil without too great injury in some other respect is desirable.

TABLE V.

MOISTURE CAPACITY OF SOILS.

	Water Capacity		Amount of Available Water		
	Min. per cent	Max. per cent	Per cent	Cu. in. per cu. ft.	Depth, inches in top 4 ft. of soil
Light Sandy Loam Early Truck Soil....	3	8	5	122	3.4
Silt Loam Bluegrass Soil...............	15	25	10	218	6.0
Clay Black Cretaceous Prairie Soil......	23	40*	17	274	7.6

(From "The Principles of Soil Management," Lyon & Fippin.)

Moisture Content and Crop Production: The amount of moisture necessary for crop production varies greatly with the soil texture and structure, the crop and the climate. Lyon and Fippin state in their text, "The Principles of Soil Management," that "—other things being equal, more water will be required in an arid region than in one of humid climate; more in a warm region than in a cold region; more in a clay soil than in a sandy soil; more in a windy section than in a region of still atmosphere; more with a high soil-moisture content; more on a poor soil; and lastly, more water is used per pound of dry matter produced in a small crop than is required in a large crop. Not only is the total seasonal requirement to be considered, but the maximum demand of the crop at any period of its growth must be met."

Investigations by Hunt and by King show that one acre of corn in Illinois will, in July, take 1.55 inches of water from the soil in one week. This indicates the large amount of water required by this one crop. The other crops common to Iowa agriculture, unless it be grasses, all require more water than does corn for the total crop growth.

Professor King of the University of Wisconsin has determined that the average crop under the best management requires water equivalent to 3.7 to 15 inches of rainfall for the average yield. From Table

*Assumed.

V it is seen that the surface four feet of even the clay soil does not hold quite one-half enough moisture for some crops, while the other two soils hold even less. This means that for an average yield the average crops require that the moisture content of the soil shall be replenished during the growing season.

13. **Forms of Soil Moisture.** Soil moisture is of three different classes: (1) Gravitational water, or that which is free to move under the influence of gravity; (2) Capillary or film moisture, which is held, by surface tension, against the influence of gravity; and (3) Hygroscopic moisture or that which condenses from the atmosphere upon the surface of the soil particles. Fig. 4 shows the proportional amounts of these forms of moisture in a soil and the availability of each for plant use.

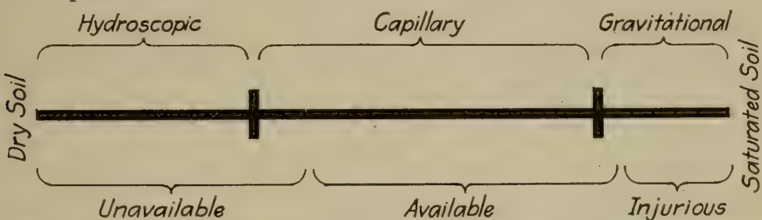

Fig. 4. Proportional Amounts of the Three Forms of Soil Moisture.*

14. **Gravitational Moisture.** Land drainage has been aptly defined as the removal of the surplus moisture from the soil. (Usually this is only the means to an end, as the benefits of drainage are due to those actions made possible by the removal of the surplus moisture). Underdrainage is the removal of this water by artificial or natural means under the surface. As it is only the gravitational soil water which is free to move under the influence of gravity, and which is unavailable for and injurious to plant growth, the need for drainage is proportional to the amount of this form of moisture present in the soil.

When the supply of soil moisture is replenished by rainfall that part in excess of what can be held capillarily becomes gravitational moisture. As the water percolates from the surface downward the thickness of the films of capillary moisture near the plane of saturation is gradually increased till the whole pore space is filled. None of the soil moisture becomes gravitational till after the full capillary moisture capacity has been supplied. This of course takes no account of the relatively large amount of water which passes from the saturated surface through the shrinkage cracks, small root cavities and worm bores.

Gravitational Moisture Content of Soils: The gravitational water-content is directly proportional to size of the spaces and is also the difference between the total moisture content and the capillary and

*From "The Principles of Soil Management," Lyon and Fippin.

hygroscopic moisture contents. If the pore spaces become too small they may be almost entirely filled by capillarity as in the fine grained clay soils. In general it may be said that the gravitational water capacity decreases as the total amount of pore space increases, because the largest total percentage of pore space is ordinarily found in the soil having the smallest grains and the smallest individual pore spaces.

TABLE VI.

MOISTURE CONTENT OF SOILS.

Kind of Soil.	Weight Per Cubic Foot, Pounds	Pore Space, per cent	Maximum Water Capacity, per cent	Maximum Capillary Capacity, per cent	Max. Gravitational Capacity Per cent	Max. Gravitational Capacity Depth, inches in top 4 ft.
Dune Sand	80	52	40.5	10.7	29.8	18.3
Coarse Sand	81	51	39.5	10.6	28.9	18.0
Fine Sandy Loam	83	50	38.0	18.0	20.0	12.7
Silt Loam	83	50	38.0	20.9	18.9	12.1
Clay	68	59	54.5	30.4	13.9	7.3
Muck Soil	15	80	333.0	250.0	83.0	9.6

Note.—Percentages are figured by weights. (From "Principles of Soil Management," Lyon & Fippin.)

The above principles are well illustrated by the data in Table VI. It is seen here that the gravitational water capacity varies directly as the porosity until the clay is reached. In this fine grained soil the pore spaces are so small as to be more nearly filled by capillary moisture. The quantities given in the columns headed "Max. Gravitational Capacity" are the amounts which might be removed by drainage. In considering the data in the columns headed, "Max. Gravitational Capacity," it should be borne in mind that these values are for a saturated soil and represent the maximum amounts of water which are subject to removal by drainage from each of these soils. If an acre of the "Dune Sand" be saturated to a depth of over four feet, the water in this top four feet would be equal to 18.3 in. in depth over the entire acre. This amount is that which a drainage system should carry away in order to restore this acre of land to the best condition.

Some determinations were made of the percentage of porosity of the soils, in natural field condition, of the fields at Hanford, Cerro Gordo County, Iowa, to which a part of the original data in Bulletin No. 52 refers.

This value of the porosity as given by these determinations, is very nearly equal to the gravitational water content of these soils, as they had all or part of their maximum capillary water content when the determinations were made. The results of these determinations are summarized in Table VII.

TABLE VII.

GRAVITATIONAL WATER CAPACITIES OF SOILS NEAR HANFORD, CERRO GORDO COUNTY, IOWA.

Kind of Soil.	Depth of Sample Below Surface	Gravitational Water Capacity, Per cent
Black Top Soil	3 in.	18.5
Clay, a little sand	2.5 ft.	5.8
Whitish Yellow Clay	3.5 ft.	2.5
Blue Clay	4.5 ft.	6.6
Sandy Clay	3.0 ft.	13.9
Sandy Clay	4.0 ft.	18.6

As is shown in Fig. 4 only a very small part of the gravitational moisture in the soil is available for plant use, and the major portion of it is injurious to vegetable life. Below the plane of saturation it completely fills the pore spaces in the soil, thus excluding the air. Many authorities on agriculture contend that aeration, or the passage of air through the soil, is one of the most important factors of crop production as far as it is controlled by the condition of the soil.

Watertable: The surface of the gravitational water in the soil, or the surface of the saturated layer, is commonly called the watertable. It is also referred to as the groundwater level, groundwater in this sense meaning gravitational soil moisture, or surplus moisture.

It sometimes happens that the presence of air in the soil causes two planes of saturation. After a rain there are sometimes a saturated surface layer and a true groundwater level at a greater depth. The pore spaces of the intermediate layer of soil are filled with air which excludes the water till such time as the air can pass out through the upper saturated layer. Figure 5 illustrates this condition as shown by an experiment by Professor King. The arrows indicate the movement of both the water and the air; as soon as the surplus water in the saturated surface layer has worked down to the readjusted true watertable, the surface of the latter will not curve upward toward the experimental well as is shown in the diagram. Under the conditions illustrated the water is passing from the well to the lower saturated layer, hence the upward curve of the watertable near the well.

Between periods of rainfall the movement of capillary soil moisture is from the watertable upward. In this one particular, that of furnishing a source of supply for capillary moisture, the gravitational moisture is very beneficial.

15. **Capillary Moisture.** In so far as plant life is concerned this is the most valuable form of soil moisture and, in fact, the only form which is available for the sustaining of plant growth. It is held, against the force of gravity, in the small pore spaces between the soil grains and as a thin film surrounding each individual particle or group of particles. Every one has noticed the rise of water in a small bore glass tube when the lower end is immersed in water, the height to which the water rises increasing as the size of the opening in the tube decreases. It is the same force, surface tension, which holds the capillary water in the soil.

Capillary-Moisture Content. In the field the grains of soil are surrounded by connecting thin films of moisture and the finer the soil particles the greater the surface area which holds this film of moisture. This variation of the capillary moisture capacity of soils with different sized grains is illustrated by the data in Table VI, already referred to.

An idea of the amount of water held in this film, and the thickness of the film, may be obtained by considering the fine clay soil where

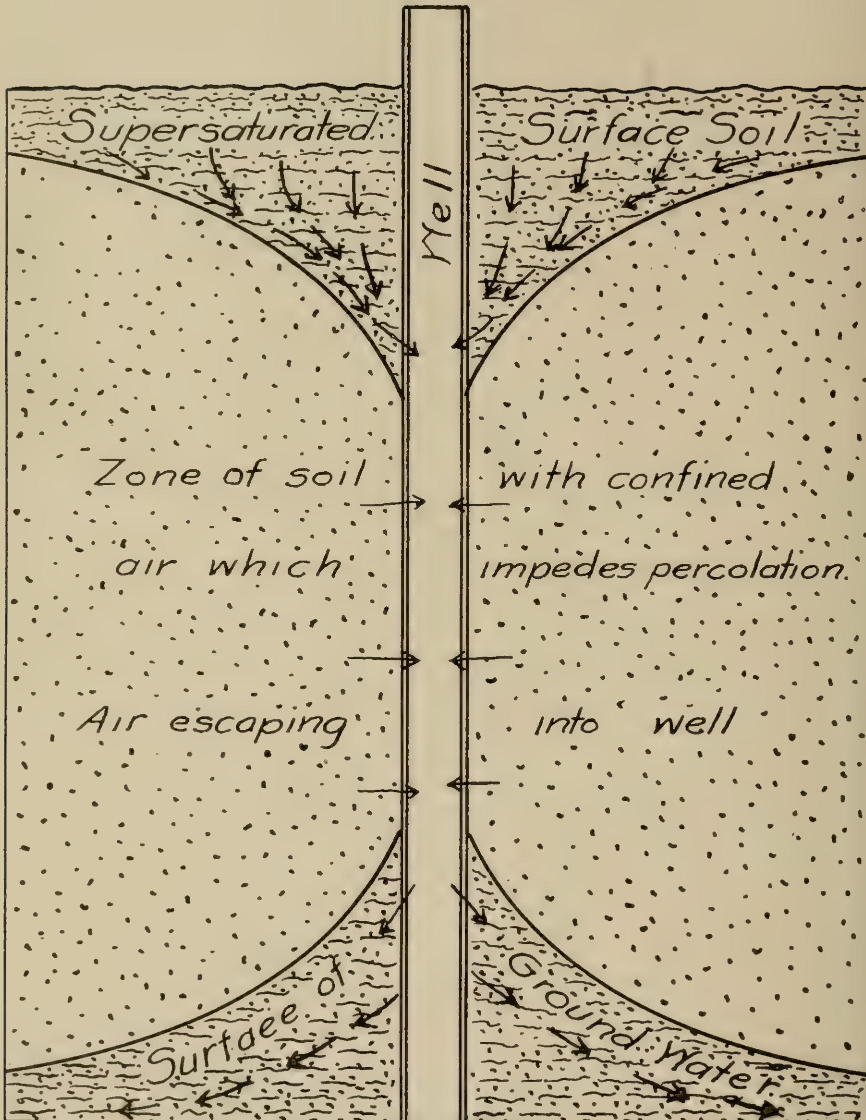

Fig. 5. Diagram Illustrating the Condition Obtaining After a Rain When the Soil Pores Are Filled With Air.

the effective diameter of soil grains is 0.005 m.m. or less. Professor King has determined (See Table IV) that for 1 cubic foot of such soil the area of the surface of the soil grains is 173700 sq. ft. or approximately four acres. Water equivalent to four inches in depth over one square foot could be held in one cubic foot of this soil if the thickness of the film was $\frac{4}{173,000}$ inches, or about one-half the thickness of a soap bubble just before it expands to the bursting point.

Available Capillary Moisture. However, not all of even the capillary moisture is available for plant use. A certain portion of it is held so intimately that the small roots cannot draw it from the soil. This fact is illustrated by the data in Table VIII, which is compiled with data given in Lyon and Fippin's "The Principles of Soil Management." The values in the column headed "Approximate % of Moisture at which Crops will Wilt," are the amounts of water which are held so intimately in the soil as to be unavailable for plant use. The sum of the values in this column and those of either the succeeding columns represent very approximately the total combined capillary and hygroscopic water capacities of those soils to which they refer.

TABLE VIII.

AVAILABLE MOISTURE IN SOILS.

Kind of Soil.	Dry Porosity, Per cent	Approximate Per cent of Water Crops Will Wilt	Available Moisture Per cent	Available Moisture Depth inches in top 4 ft.
Dune Sand	52.2	3.0	7.7	4.6
Coarse Sand	51	3.0	7.6	5.2
Fine Sandy Loam	50	5.0	13.0	8.5
Silt Loam	50	10.0	10.9	6.9
Clay	59	17.0	13.4	7.0
Muck Soil	80*	80.0	170.0	20.5

Capillary Moisture and Drainage. Capillary moisture has no direct relation to underdrainage though it has a very definite and important bearing upon the results and effects of drainage. When the plane of saturation is lowered by the use of underdrains the moisture necessary for crop production must be supplied by capillarity.

16. **Hygroscopic Moisture.** This is the least important of the three forms of soil moisture and in amount it is relatively very small. It is the moisture which condenses from the air onto the soil grains, the condensation taking place either at the surface or in the soil, if it be so open as to allow of a circulation of air.

Hygroscopic-Moisture Content. The amount of this form of moisture in a soil is a function of the surface area exposed and consequently is greater in the finer grained soils. The amount also varies inversely as the temperature in the soil. Table IX shows the amounts of hygroscopic water held by three soils, each of which was a soil separate obtained by careful analysis.

*Assumed.

TABLE IX.

PER CENTS OF HYGROSCOPIC MOISTURE AT 21°C., OR APPROXIMATELY 70°F.

Very fine sand	1.8
Silt	7.3
Clay	16.5

Taken from "The Principles of Soil Management," Lyon & Fippin.

Comparison of these data with others in the text from which these were taken show that all soils hold a considerably larger percentage of capillary water than of hygroscopic water. The importance of this form of moisture is further reduced by the facts that it is varying in amount and unavailable for plant use. It has practically no bearing at all upon the underdrainage of the soil.

17. **Loss of Soil Moisture.** The total amount of moisture in the soil at any one time is a function of the supply and the loss. The supply may be either from rainfall or from percolation from higher ground; the loss will be from percolation, evaporation or transpiration of plants. Relatively the loss by percolation is much larger than either or both of the other two. As a general rule it may be said that where the soils are such that percolation is very slow the losses by evaporation will be high comparatively.

The loss due to percolation naturally has to do with the movement of gravitational water so will be discussed under the head.

The losses due to evaporation are in the nature of thermal movements and will be discussed under that head.

IV. SOIL-WATER MOVEMENTS

18. **Soil-water Movement and Drainage.** The relations of the different movements of soil water to underdrainage are the same as those of the forms of soil moisture to which they refer. The gravitational movement, or the percolation of the groundwater, is the one by which the surplus water reaches the drain, and is, consequently, the most important in this connection. Just as capillary moisture has an important relation to the effects of underdrainage, so has the capillary movement, as it is the effectiveness of this movement which determines whether or not the underdrained soil shall be constantly supplied with the moisture necessary for plant growth.

19. **Forms of Soil-water Movement.** The previous discussion of the types of soil water will readily suggest the forms of soil-water movements. Each of the three forms of soil water has a distinct type of movement. These movements are: (1) Gravitational, or the movement of gravitational water under the influence of gravity; (2) Capillary, or the movement of capillary moisture due to capillarity or surface tension; and (3) Thermal, or the movement due to changes in temperature. This latter movement is in the form of water vapor, though changes in temperature have some effect upon the other two types of movement.

These three types of soil-water movement will be discussed in the reverse of the order in which they were stated. Because of its very important and direct relationship to underdrainage the discussion of gravitational movement will be left till the last then be given more attention than the other two.

20. **Thermal Movements.** This movement takes place as the movement of water vapor and consequently is relatively very small. If the bottom of a column of soil be heated, the cold portion directly above the heated portion will be found to have added moisture. The moisture from the heated layer has been converted into water vapor and as such has passed up through the heated soil to the cold portion where it has been recondensed. If none of this soil column had been cold enough to condense this vapor it would have passed upward and outward to the air. Such an action would have resulted in the loss of soil moisture by evaporation.

Evaporation. Evaporation of soil moisture may take place not only at the surface as is popularly supposed but also in the deeper pores of the soil. When a dust mulch is maintained the evaporation is very apt to take place at the surface of the moist layer. The loss due to this movement depends upon the rate at which diffusion into the atmosphere takes place. Buckingham found that the loss due to evaporation from sandy, silty, or clayey soils where the porosity was near 50% varied from 4.3 inches per year for the sandy soils to about 1 inch per year from the clayey soils. In the ordinary agricultural soils of Iowa this loss is so small as to be of very little importance in a study of soil moisture as related to underdrainage.

21. **Capillary Movement.** In the discussion of capillary soil moisture, its importance to plant life and its relation to underdrainage were explained. Its movement naturally bears the same relation to these as the moisture itself. It is of vital importance to crop production but of very little importance to the operation of underdrainage.

Form of Movement and Factors Governing It. The form in which capillary moisture occurs in the soil has been explained as a thin film of moisture surrounding the individual soil particles. Its movement then is a film movement and depends upon an unbalanced condition in the pull exerted upon these films. Any moisture which is moved in this way naturally moves as a film and consequently is small in amount. This movement always takes place from the wetter soil to the dryer regardless of the direction.

The soil factors governing this movement are texture, structure and dampness. The finer the soil particles the more surface is exposed and consequently the greater capillary pull is exerted. In general it may be said that the extent of capillary movement is inversely proportional to the fineness of the soil grains. It is also true, that when the soil grains are very fine the spaces between them become so very minute and the thickness of the film of moisture so reduced as

to so increase the friction that the movement is very slow. It is also necessary for water to wet any substance to which it is held by capillarity, hence if the soil particles are somewhat dry the moisture is not held to them strongly until after they become damp, as all natural field soils have a certain resistance to wetting.

The rate and extent of this movement are also affected, to some degree, by the temperature changes. The surface tension is greater for low temperatures than for high, causing both a greater rate and a greater extent of movement at the lower temperatures. On the other hand, warm water is more limpid than cold and will consequently pass through the small pore spaces more readily.

Relation of Capillary Movement to Underdrainage. The most important phase of this movement in relation to underdrainage is the distance which a sufficient quantity of water for crop production will be raised. It is the effect of any drainage to lower the permanent watertable after which the moisture for sustaining plant life must be furnished capillarily. If the watertable is held at too low a stage an insufficient amount of moisture will be raised to the upper soil layers and the crops may suffer. In such a case the underdrainage system will have been too effective and its results will be no better than those conditions which obtained before any drainage was attempted.

Rate and Extent of Capillary Movement. As has been stated the rate and extent of capillary movement depend upon the distance the water is raised and the nature of the soil through which the movement takes place. In Part II of the 19th Annual Report of the United States Geological Survey is given experimental data from which Table X was compiled. These data illustrate the principle that the rate of movements varies inversely with the extent and distance of the movement. The lower rate of movement in the clay soil from each lift is probably due to the greater friction and greater resistance to movement in the finer grained soil.

TABLE X.

POUNDS OF WATER PER DAY PER SQUARE FOOT OF SOIL RAISED FROM DIFFERENT DEPTHS.

Soil.	Depths 1 foot	2 feet	3 feet	4 feet
Medium Fine Sand	2.37	2.07	1.23	0.91
Medium Clay Loam	2.05	1.62	1.00	0.90

The report referred to above states further that though there were very few reliable data on this subject those at hand indicated that for natural field soils the movement is fairly rapid when the lift does not exceed four feet. If the rate given for that lift in Table X be maintained throughout the year a quantity of water equivalent to 63.8 inches in depth would be raised. Experiments already referred to show that corn in Illinois used water during July equivalent to a depth of 1.55 inches or 1.15 pounds per square foot per day. When this moisture is to be supplied by capillarity, as is the case during periods between rains, the lift should not exceed 2.5 to 3.0 feet, if the crop is

to be fully supplied. It has also been previously stated that for the average yield under the best methods of cultivation the average crop requires from 3.7 to 15 inches in depth of moisture or from 19.24 to 78 pounds of water. If the average growing season be taken at 80 days this would mean that from .24 to .96 pounds of moisture would be required per day per square foot. This data in Table X indicates that to meet this demand the lift for capillary moisture should be about 4 feet. However, the amount of moisture needed by a crop varies so greatly with stage of its growth and with the season that the above figures can be only approximate.

Capillary Movement and Depth of Underdrains. From the standpoint of the supply of capillary moisture the above data indicate that the ideal underdrainage system for the average Iowa soil which is to be used for the ordinary field crops is one which will maintain the groundwater level at a depth of from 2.5 to 3.0 feet below the average elevation of the crop roots. However, this optimum depth varies slightly for the various crops and soils. This depth seems to afford the maximum storage capacity without so lowering the watertable as to reduce the capillary movement too greatly. There are, however, other factors than the supply of capillary moisture which must be considered in determining the depth of underdrains.

22. **Gravitational Movement.** *Form of Movement:* It was stated in the discussion of gravitational soil water that the need for drainage was directly proportional to the amount of this form of moisture present. Consequently, the nature and rate of this movement will be a very important factor, and in most cases the deciding factor, in the design of the underdrainage system. It is true that the optimum position of the watertable with relation to capillary movement should be considered, but it is probable that the rate at which the surplus, or gravitational, water is removed will be of greater importance.

The gravitational movement is the result of the gravity pull upon the soil water, and, as both the capillary and the hygroscopic moisture are held against gravity, it is only the gravitational soil moisture which is affected. This moisture and its movement are usually referred to as "groundwater" and "groundwater movement" or "percolation."

The direction of this movement depends entirely upon the soil formations. Being a gravity movement the direction is always as nearly vertically downward as the soil conditions will permit. From the previous discussions of soil composition and formations it will be readily seen that the channels afforded by the soil pores will not be straight and where the percolating water encounters a more or less impervious layer the direction may be so changed as to have only a very slight slope; or if the percolation is through a porous layer between two nearly impervious layers which are undulating or which approach the surface closely, the movement may be upward, as in the case of the outlet to a spring.

Channels for Movement. In all natural field soils the percolation of the groundwater, especially downward from a saturated surface layer, occurs in two ways; through the soil pores and through the shrinkage cracks, small root cavities and worm bores. The movement through the soil pores is subject to both theoretical and experimental investigation. The flow through the comparatively large channels afforded by the shrinkage cracks, etc., is indeterminate. The presence of these openings can be detected in the soils of any field, but the amount of channel capacity thus afforded could be determined only by a great number of careful mechanical analyses. The rate of flow through these larger openings is comparatively great because they afford a much more efficient channel.

The following discussion of groundwater movements will be confined entirely to the flow through the soil. In a later discussion of runoff from underdrained areas the total flow through the soil, both through the soil and through the large channels mention, will be considered.

The flow of water through the channels afforded by the pores of the soil is subject to the same laws as the flow through a pipe, a tile drain or an open ditch. In each case the velocity of flow depends upon the slope and the resistance which the sides of the channel offer to the passage of water. The rate of flow is the product of the velocity and the cross-sectional area of the moving stream.

The size, shape and hydraulic efficiency of the soil-water channels depends upon the texture and structure of the soil. However, while these are the only soil factors influencing the movement of gravitational soil water, some external forces have a definite influence upon the rate of this movement.

Effect of Temperature and Barometric Pressure. Changes in temperature affect the rate of movement both through the effect upon the air and upon the moving water. Likewise the barometric pressure tends to increase or decrease the rate of flow as the barometer rises or falls. The wind may cause a suction or an increased pressure at the outlet, the flow being effected accordingly.

The exact amount of the affect of temperature upon the rate of percolation of soil water, except for the effect upon the water itself, is indeterminate, though it may be approximated by experimentation. A lowering of the temperature of the soil air will cause it to contract causing a suction which tends to hold the soil water. An abrupt warming of the soil air will have the opposite effect. Consider, for example, the conditions obtaining in a well underdrained soil. In the evening the outer air cools much more rapidly than that in the soil. This cooler air is the denser and flows to the more rarefied and warmer air in the soil. When the cool outer air passes from the tile into the soil, the soil air cools and contracts causing a suction which tends to hold the soil water. In the morning the outer air warms more rapidly than the soil air, and due to the circulation within the tile and the soil, the soil air is warmed, causing it to expand and tend to

force out the soil water. In the 19th Annual Report of the United States Geological survey are given some records of the variation in the rate of discharge from a tile drain due to the change in temperature during the day. When the rates of discharge and temperature are plotted as curves they are found to be approximately parallel, the rate of discharge increasing during those hours when the temperature should be expected to increase and decreasing towards evening. It should be borne in mind, however, that these changes were due to the effect of temperature change upon both the soil air and the outer air and upon the water itself.

The variation in the rate of discharge from a tile drain or a spring, due to barometric changes, is very similar to that due to temperature changes. The rate of flow increases and decreases as the barometer rises and falls. The changes in the pressure in the outer air are transmitted through the tile to the soil air causing a suction or pressure as it contracts or expands. In the same publication referred to above are given curves showing the change in rate of discharge from underdrains and springs and the barometric changes for the same periods. In each case the curves are nearly parallel except that the changes in the barometric pressure occur more rapidly than the changes in rate of discharge. Professor King found from these records that the effect of changes in barometric pressure were sufficient to vary the rate of discharge as much as 8% for springs and as high as 15% for underdrains.

The changes in rates of groundwater movement due to temperature and barometric changes are interesting rather than valuable in a discussion of underdrainage. The changes due to each are usually comparatively small and are compensating. The present knowledge of the movement of water in the tile and of other factors of drainage engineering is not sufficiently accurate to demand any changes in the design of an underdrainage system to care for the variations from these causes. It is probable, however, that for extremely large underdrained areas this variation in the rate of flow would be noticeable, especially if accurate discharge records were kept.

Effect of Soil Texture. The influence of the texture of a soil upon the movement of groundwater is due to the variation in the size of the soil pores resulting from differences in the sizes of soil grains. The finer the soil grains are the smaller the pore spaces and, consequently, the higher the resistance which they offer to the passage of percolating water. The rate of percolation varies directly as the size of the soil grains until in some very fine grained soils the pores become so small as to be completely filled with capillary moisture.

As has been stated the movement of gravitational soil water is governed by the same laws as the flow through a pipe under gravity head. In the pipe the velocity of flow is determined by the slope and the resistance which the pipe offers against the passage of water. This resistance, considering only that within a straight pipe, is due to the friction between the water and sides of the pipe and so varies directly

as the wetted area of pipe surface. From the laws of the variation of the area and circumference with the diameter, it is readily seen that the resistance in a small pipe is proportionally much greater than that in a large pipe.

The application of the above principles to the movement of water through soils may be illustrated by considering Fig. 3 as representing sectional views of soils and considering each grain as a cylinder of unit length and of the same diameter as the spherical soil grains. If the diameters of cylinders arranged as shown in Arrangements 1 and 2 of Fig. 3 be taken as 1 inch and ¼ inch, respectively, the cross-sectional area of the pore spaces will in each case be 3.4336 square inches, while the surface area of these pores will be 50.2556 square inches and 201.0224 square inches respectively. In other words, decreasing the diameter 4 times leaves the total cross-sectional area of the pore space the same but increases the surface area 4 times and, if the frictional resistance be taken as the same per unit of area in each case, the resistance is 4 times as large with the small grains as with the larger.

The above discussion is of general principle only, when applied to soils in natural field condition, because there the grains are not arranged in any such regular order and are not of uniform size. But the principle that the ratio of the exposed surface area to the cross-sectional area of the pore space increases at a more rapid rate than the diameter of soil grains decreases holds true, though this ratio may vary considerably. It is these ratios which will determine, to a large extent, the ratios of the flows through different soils. Every one has noticed how much more quickly the water left upon a loose sandy soil will disappear than that left upon a field of close grained clay soil. This is only an illustration of the above principles.

Effect of Structure. The effect of different arrangements of soil grains upon the rate and extent of the movement of groundwater is governed by the same principles as that referring to the effect of various sized soil grains. If the arrangement is such as to give a large exposed surface area in proportion to the cross-sectional area of the pore space the flow is small. If the same assumption be made as in considering the soil grains of 1 inch and ¼ inch diameters in the preceding paragraph, grains of 1 inch diameter and arranged as in Arrangements 1 and 3 of Fig. 3, the cross-sectional area of each pore will be .2146 square inches and .04 square inches respectively. In other words, the area of the pore space for 1 inch grains arranged in columnar order is 5 times that for the same sized grains arranged in oblique order. The areas of the exposed surfaces in these two cases, considering each grain as a cylinder of unit length, are 3.1416 square inches and 1.5758 square inches respectively. The ratio of the exposed surface to the area of the pore is 14.6 for the columnar arrangement and 39.4 for the oblique order. It is thus seen that with the oblique arrangement the pore space is both smaller and less efficient than in the columnar arrangement.

In the section on "Soils" the property of some soils to form granules, or groups of grains, was discussed. As far as the percolation of groundwater is concerned, a soil of granular structure is a large grained soil, and, as such, allows a much more rapid groundwater movement than it would if composed of the individual grains. There are some small pore spaces within the granules themselves but these are so small as to allow of only a very small flow in comparison to that passing through the pores between the granules.

The Viscosity of the Moving Water. The effect of temperature upon the movement of gravitational water is of considerable importance. The viscosity of water decreases as the temperature rises, and, consequently, the flow increases with the temperature of the water. Hazen found in his experiments with filter sands that the relative flow at different temperatures varied from .70 at 32° to 1.0 at 50° and 1.45 at 77°. All temperatures were measured in degrees fahrenheit. In other words, raising the temperature from 32° to 77° approximately doubles the flow. This fact more than anything else, accounts for the variation in the flow from tile drains. However, the temperature within the underdrained soils varies much less than that of the air. It is probable that during the growing season in Iowa the temperature of drained soils is very nearly constant at 50° fahrenheit. At least, if temperature were to be taken into account directly in computing the flow through Iowa soils, it would seem safe to make such calculations with a soil temperature of 50°F.

23. **Do Tile Drains "Draw?"** How far will a tile drain "draw?" The statement that the underdrains in one field "draw" better, or farther, than those in another field is often heard. Actually the drains do not draw at all, if by "draw" it is meant that the tile exert a pull tending to suck the water out of the soil pores and into the drain. The underdrains serve simply as a collecting channel, or outlet, for the percolating water. If one field is drained farther back from the line of tile than another field it signifies simply that the conditions as to depth and capacity of the tile, or of the soil are such as to cause a more ready movement of the groundwater in the one case than in the other.

How Water Moves from the Surface to the Drain. It is the opinion of many persons, who have given the subject little serious consideration, that the water falling upon the surface of an underdrained area moves in a diagonal direction till it is directly over the tile and then enters it from the top. This is not the case, as no water ordinarily enters the tile from the top except that which falls upon the surface directly above the drain and then only when the soil conditions are such as to allow of a nearly vertical percolation.

The path taken by a drop of water passing from the surface to the drain is illustrated by Fig. 6. The surplus water in the surface layers passes as nearly directly downward as soil conditions will permit until it reaches the watertable, and then moves laterally so as to enter the drain from the bottom. Its movement after reaching groundwater

level is somewhat uncertain, but the paths illustrated in Fig. 6 are the general paths of this movement. The water below the plane of saturation is under a certain hydraulic or hydrostatic head and follows the path of least resistance, which, in this case, is into the drain. The only case when water generally will enter the drain from the top is when the tile is or has been surcharged and the soil above has become saturated.

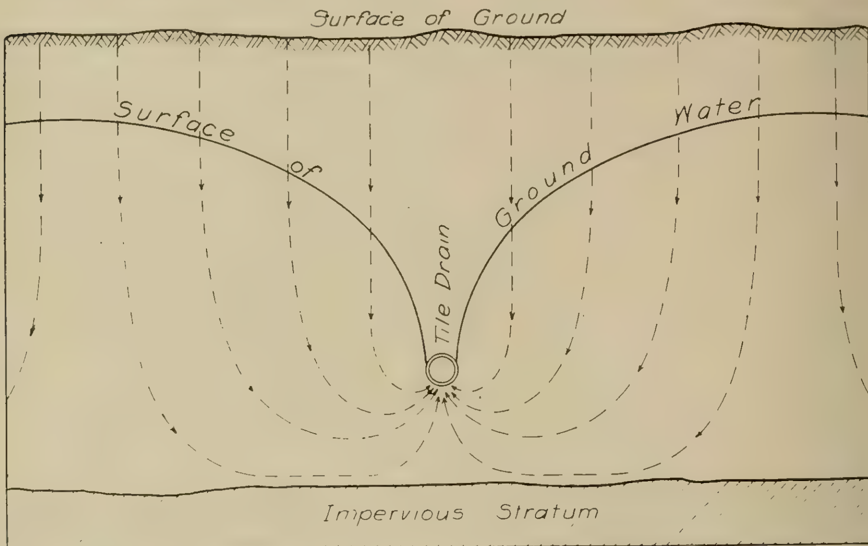

Fig. 6. Diagram Illustrating the Movement of Water from the Surface to the Drain.

24. **Natural Underdrainage, Seeps and Springs.** An area is said to have natural underdrainage when there is a subsoil stratum of sand or gravel at a depth of from 2′ to 6′ below the surface. In such area the surplus water from rainfall may pass down through the top soil to this sand layer and through it to an outlet. The thoroughness of such drainage depends upon the readiness with which the surplus water in the top soil layer reaches the layer of sand and the rate at which it passes away through this sand layer.

However, such lands, especially if they are very flat, usually require artificial underdrainage if they are to be efficiently drained. If the top soil is fairly loose and porous and if the said substratum is not at too great a depth, say from 4 to 5 feet, the drains may be placed at the top of the sand stratum and at considerably greater distances apart than if placed in the top soil. Care must be taken in such design to see that the tile are well supported whenever placed in any sand stratum.

Every one has noticed seepy or spouty spots on the sides or at the foot of the steeper slopes. These wet places are especially evident where there is a porous layer overlying a stratum of very close clay, both of which outcrop upon the slope. The surplus soil water works down into the porous layer and then follows it to the outcrop, that being the only outlet. In some few cases these wet places are caused by the flow from a porous layer which is both overlain and underlain by impervious layers. In this case the soil water enters the porous layer at a point higher up the slope where the overlying impervious layer is very thin or above the point of its beginning.

The drainage of these wet spots is accomplished by tracing the porous stratum for a few feet back from the outlet and then constructing intercepting tile drains. In some instances the drains may be laid at a sufficient depth in the wet areas so as to intercept the seep water as it rises to the surface.

Springs, as they are ordinarily considered, are not usually a factor to be considered in the design of underdrainage. The location is generally such that the flow will not interfere with any cultivatable lands and, as the flow is more often than not a fairly constant quantity, provision for them can be made without difficulty.

The character of the soil formation causing springs is very similar to that causing the second class of "spouty" spots mentioned in a preceding paragraph. In cases where a spring causes conditions demanding relief by underdrainage, an intercepting drain is necessary if the flow is to be prevented from coming to the surface.

25. **Rate of Groundwater Movement.** Several investigators have endeavored to express the laws governing the flow of water through soil, or other porous media, in a mathematical formula. Such formulas contain constants or factors representing the character of the soil (as the fineness of soil grains, and the porosity), the length and cross-sectional area of the column of soil through which the flow occurs, the loss of head in passage and the temperature, or the viscosity, of the moving water. In one formula all of these factors may be represented by separate quantities while in others one or more of the soil factors and the temperature factor may be represented by a constant.

These formulas, in their original form, are unsuited for application to drainage work because of their great refinement. To be practically and readily usable a formula for drainage uses will require no data which are not easily obtainable and will not be more accurate than the original data or the other formulas which will be used in the design of the system. The effective size of soil grain for a given sample of natural soil can be determined only by a careful laboratory analysis, which is both impractable and undesirable in drainage design. Such an analysis would give data of a much greater degree of refinement than the other data which will be used in the design. Much the same thing is true also of the determination of the porosity, if the absolute value is to be determined, though the space available for the move-

ment of the surplus moisture can be determined without great difficulty.

*Darcy's Formula.*One of the earliest attempts to determine, and state, the laws of the flow of water through soils was made in 1856 by Darcy, a Frenchman. He announced that the flow of water in a certain direction through a column of soil is proportional to the difference in pressure at the two ends of the column and inversely proportional to the length of the column.* Darcy expressed his conclusions in the formula $v = k \frac{p}{h}$

where v=the velocity of the moving water.
p=the difference in pressure at the two ends of the column.
h=the length of the column.
k=a constant whose value depends upon the character of the soil, especially the size of the soil grains, and which must be determined experimentally.

The principles expressed by Darcy has been incorporated in all subsequent formulas for the movement of groundwater. In reality, Darcy did no more than say that, other things being equal, the rate of flow was proportional to the hydraulic grade which is true of the movement of water under all conditions.

Mr. Allen Hazen, Consulting Engineer, of New York, has derived a formula for the movement of water through filter sands. His formula is the same as Darcy's with added factors representing the effective size of soil grains and the effect of temperature. According to Mr. Hazen's statements his formula is true for only sands with grains within certain limits of size, the lower limit being much larger than the grains of natural field soils.

Mr. Charles S. Slichter of the United States Geological Survey has derived a theoretical formula for the movement of water through porous media. As far as is known, Mr. Slichter's formula* is the only purely theoretical investigation of this subject which has ever been published. His theoretical derivation was made in conjunction with an experimental investigation by Prof. F. H. King, of the University of Wisconsin. In some trials, the flow through certain soils was computed by Mr. Slichter and measured in the laboratory by Mr. King. These results gave such close checks as to prove that this formula was correct if used for soils which had been accurately analyzed. This formula requires so careful a laboratory analysis of the soil through which the movement is to be calculated as to prohibit its use in drainage work.

26. **Relation of Groundwater Movement to Underdrainage.** Since only gravitational moisture, or groundwater, is free to move under the influence of gravity, this is the only moisture which can be re-

*U. S. Geological Survey, Water Supply Paper No. 67.

moved by the drains. The rate of its movement through the soil to the drains is the controlling factor in determining the efficiency of the drainage. The primary function of the underdrains is to make possible this movement by providing an outlet for it.

According to Darcy's principle, the velocity of the movement of water through a particular soil depends upon the hydraulic slope of the moving water. It follows then that any change in the lateral system which causes a change in this hydraulic slope will cause a corresponding variation in the velocity of the movement of the groundwater that is flowing through the soil to the drains. As the rate of this movement determines the efficiency of the drainage, it follows that the lateral system should be so designed as to give the desired control of this movement, or of the rate of removal of the surplus moisture. In other words, the spacing and depth of the laterals in a particular field controls the rate of the movement, and of the removal of the surplus moisture, and this in turn determines the volume of flow which determines the capacity required in the mains and submains.

The application of Darcy's principle to the design of underdrainage systems may be summarized in the three statements given below. Each of these is based upon the premise that all factors, except that stated as a variable, remain constant. From the nature of the problem, it naturally follows that the converse of each of these statements is equally true.

(a) The rate of the movement of the groundwater to the drain varies inversely with the distance between the laterals.

(b) The rate of this movement varies directly with the depth of the underdrains (actually varies with the vertical distance from the crest of the watertable to the water in the drain).

(c) The rate of runoff from the underdrainage system varies directly with the rate of the movement of the groundwater to the drain.

The first two of these principles will be discussed in the following paragraphs. The relationship of the spacing and depth of laterals to the rate of runoff will be taken up in succeeding articles.

Effect of Spacing of Laterals. Darcy's principle states that the velocity of water moving through any given soil varies directly with the hydraulic slope of the moving water. (In this connection the hydraulic slope is the quotient obtained by dividing the vertical distance from the crest of the watertable, or plane of saturation, to the free surface of the water in the drain by the horizontal distance between these two points.) This means simply that if the distance between the laterals be decreased, other conditions remaining the same, the hydraulic slope of the moving groundwater is increased and that it will move to the drain at a more rapid rate. This will tend to remove the surplus moisture at a more rapid rate which, in turn, means that the soil is in the condition required for proper plant growth a larger percentage of the time. This increase in the rate of the movement of

groundwater also requires that the mains and submains of the system be designed to care for larger flows. Suppose, for example, that the drains in a particular field are 100 feet apart. If intermediate drains were constructed so that laterals would be only 50 feet apart, the rate of flow to the drains, for any position of the watertable, would be just twice that when the drains were 100 feet apart.

The form of the surface of the plane of saturation, or the watertable, has already been explained. Fig. 7 illustrates the condition just described. The lines D and E represent two positions of the watertable when only drains A and C are constructed. After the intermediate drain B has been constructed, the positions of the watertable are illustrated by lines F, G, H and I. It can be seen from this diagram how the hydraulic slope of the water moving to the drain is made steeper by decreasing the distance between the laterals.

This diagram also illustrates the way in which the closer laterals cause an increase in the area of soil which is free from surplus moisture. The importance of this latter fact is emphasized by the fact that plant roots can neither live nor draw food from a saturated soil.

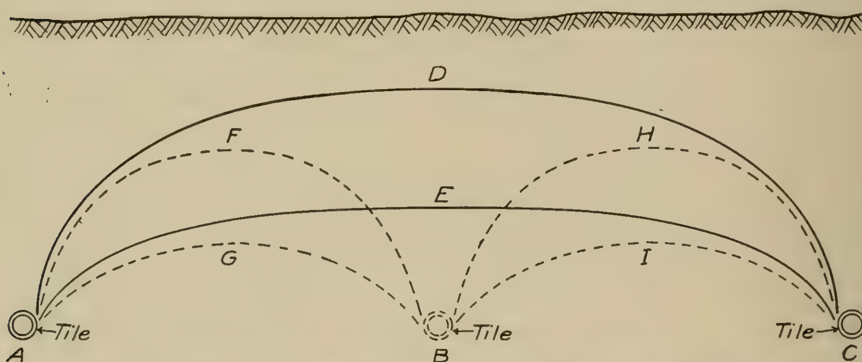

Fig. 7. Diagram Illustrating Effect of Closer Spacing of Laterals.

The form of the watertable between drains and the rate of movement of groundwater will vary with differing soil conditions. The relationship discussed above cannot be applied directly to systems in different fields. If the soil conditions are similar approximately correct comparisons can be made. This principle is of more value in considering the various systems that might be used in one field and in explaining the general proposition of the relative efficiencies of different underdrainage systems.

Effect of Depth of Laterals: The discussions just given will explain the relationship between the depth of laterals and the rate of movement of the surplus soil water. Few, if any, underdrainage systems are so designed and constructed that the plane of saturation will not

rise to the surface during or after heavy rains. It is apparent then, that if the soil is uniform, that placing the laterals deeper will cause an increase in the rate of movement of surplus moisture as will a decrease in the distance between laterals. However, other considerations control the depth of laterals to within such close limits that this relationship is of less importance than that of the spacing in laterals.

In considering the effect of placing the laterals at a greater depth the effect of the variation in the soil at different depths must be considered. For example, if the subsoil is a very close clay, the movement of groundwater though this stratum will be much slower than through the more open top soil. This increase in the resistance to the flow may be sufficient to more than counterbalance the increase due to the steeper hydraulic grade. In some soils, such as were referred to above, drains only two feet deep may appear to be just as effective, or in extreme cases, more effective, than drains four feet deep. A greater depth than this is desirable in order to increase the depth of soil that is in condition to furnish plant food. This close subsoil usually contains valuable plant food which must be made available if the field is to produce the maximum crops. The close soils become more open and drain more readily after the drains have been in operation for a time, and experience shows that this improvement continues as time goes by. The solution of the problem presented by such a field is to place the laterals closer together and hold to the four foot depth.

It will be readily seen from Fig. 6 or 7 why the average position of the watertable is lowered as the drains are placed deeper. The drains cannot lower the plane of saturation below their own level, and, practically, cannot hold it to their own level during the growing season when rains are usually frequent. The plane of saturation must have an appreciable slope (the hydraulic slope upon which depends the rate of flow to the drain) toward the drain, or the rate of movement of the soil waters will be so slow as to be of small consequence. The food requirements of the crops and the plant food generally available then demand that drains be not less than four feet deep except in unusual cases. In these discussions no consideration has been given those cases where the depth of the drains may be controlled by construction features, this discussion being confined to the relationship of the depth of the drains to the rate and extent of the removal of the surplus soil moisture.

The Time Factor: The relationship of the spacing and depth of laterals to the rate of the movement has been explained. The increase in this rate which results from certain changes in the lateral system has an important bearing upon the crop production and upon the cost and degree of thoroughness of the cultivation. In each soil, each position of the watertable represents a certain amount of surplus moisture. If changes in the lateral system cause the removal of this surplus moisture at a more rapid rate, the loss due to this surplus is cor-

respondingly reduced. If the surplus moisture is removed more rapidly there is a larger average depth of soil available to support the growing crop. The removal of the surplus moisture at a more rapid rate allows the field to be prepared and the crop to be planted earlier. The more rapid removal of the surplus after each rain allows the field to be cultivated with less loss of time because the ground is too wet for proper cultural operations. In short, the more rapid removal of the surplus moisture means a decrease in the total time during which the plane of saturation is too high to permit of the maximum plant growth and proper cultural operations. This point is of especial importance when the underdrained area is to be used for truck crops.

5. RUNOFF.

27. **Definitions.** The portion of the rainfall or snowfall which passes over or through the ground to the natural or artificial drainage channels is termed runoff. It is that part which passes through the soil to the drains which is of particular interest in this discussion.

The rate of runoff is variously expressed as a percentage of the rainfall, as the depth in inches removed from the watershed per 24 hours, and as cubic feet per second, or per 24 hours, from each unit of watershed area.

It is probable that the method most common in present day drainage practice is to express the rate of runoff as the depth in inches removed from the watershed in 24 hours. This depth is often referred to as the runoff coefficient or the drainage coefficient, or in the abbreviated form of a "3/8-inch runoff." This method of expressing the rate of runoff will be used in this bulletin.

28. **Factors Affecting Runoff.** The relationship of the form of the lateral system to the rate of the movement of the surplus moisture through the soil has been explained. Since the runoff from an underdrainage system is the surplus soil moisture which flows through the soil and collects in the drain, it follows that the rate of runoff is directly dependent upon the spacing and depth of the laterals. The efficient operation of the underdrainage system demands that it be so designed that it will remove the surplus moisture at a sufficiently rapid rate; if this is not done the primary object of the construction is not attained. The climatological, topographical and physical features which determine the amount of rainfall concentrated on the area to be underdrained and the soil characteristics which determine the rate of movement through the soil, jointly determine the form of the lateral system necessary to secure the desired control of the groundwater. Those factors which are ordinarily considered to control the rate of runoff should be considered to control the type of the lateral system and then the probable rate of flow from each system should be determined as accurately as possible and used as the rate of runoff for which the capacities of the various lines of the system are designed.

The principal natural or physical factors controlling the amount and rate of movement of surplus soil moisture are: rainfall, topography of the watershed, character of the soil, evaporation and transpiration of plants and seasons and climate. The general relation of each of these to the form of the lateral system and its resulting effect upon the rate of runoff will be discussed in the above order.

Rainfall. Since rainfall is the source of supply of soil moisture, the amount of surplus moisture to be removed by the drains naturally varies with the rainfall. In sections where the rainfall is heavy, a proper control of the soil water will demand a closer lateral spacing, these conditions resulting in a high rate of runoff. The total annual runoffs from two underdrainage systems, of similar size and design, draining similar watersheds so located that the annual precipitation is 30 inches and 60 inches, will be approximately in the ratio of one to two.

However, the total amount of surplus moisture to be removed during the year is of very much less importance in this connection than is the probable maximum amount which must be removed per unit of time in order to secure proper soil conditions during the cropping season. Both the ordinary maximum daily precipitation and the rate at which it falls must be recognized as controlling factors. If the underdrainage system is to be constructed in a locality where the daily rainfall is ordinarily heavy during the cropping seasons, but consists of severe short showers, as thunder storms, the water will reach the earth much more rapidly than it can be taken up by the soil. Under such conditions much of the rainfall must necessarily flow away over the surface, with the result that there will be but a comparatively small amount of surplus moisture to be removed by the underdrains. The rate of underdrainage runoff due to a rain of one inch in one hour will often be much smaller than that due to a rain of one inch falling, slowly but steadily, in a period of six to twelve hours. In the latter case more nearly the total amount of water falling will pass down into the soil and on to the drains.

The effect of hard dashing rains was well illustrated by the records from two adjoining drainage systems in Southern Iowa, where the Engineering Experiment Station was conducting an investigation during the summer of 1914. The soil in which these drains were laid is rather close but has been underdrained sufficiently long to be much more open, and to drain more readily, than in its natural state. From early spring till the latter part of May the soil was very dry, though it had been wet when the crop, oats, was planted. The rainfall during June and July was as follows: June 10, 0.50 in.; June 13, 2.12 in.; June 22, 0.50 in.; July 6, 1.25 in.; July 12, 2.06 in., and July 16, 1.0 in. Each of these rains was a heavy downpour lasting but a short time. The water reached the surface so rapidly that a very large proportion of it passed away as surface runoff. So small a portion of this water entered the soil that at no time during June or July was there any flow

in the outlet mains of these systems. If the rate of precipitation in these storms had been slow it is very possible that after the rains of July 12 or 16, the outlet main would have been flowing full.

In the design of an underdrainage system consideration should be given to all the factors which tend to control the amount of surplus moisture to be removed by the drains, and the rate at which it moves through the soil to them. Where the rainfall is such as will ordinarily cause the saturation of the soil to a high level during a considerable period, the spacing of the laterals must be such as will cause a rapid movement of the groundwater to the drains and the runoff coefficient used in calculating the sizes of the tile required must be correspondingly large.

Topography of the Watershed: The area and slopes of the watershed have a very great influence upon the amount of surplus moisture to be removed by the drains. If the slopes are steep a large part of the rainfall passes away over the surface. If the underdrained area is a flat with an untiled tributary area with steeper slopes, a portion of both the surface and natural underground runoff from the tributary area will be collected in and on the flat. This condition is the same in effect as subjecting the flat to heavier rainfall. The amount of such increase will depend upon the slope and proportional area of the tributary watershed. The effect of such additions upon the design of the lateral system and upon the rate of runoff has already been discussed in the previous paragraphs.

The size of the underdrained area, unless it be very large, will usually have but little effect upon the rate of runoff. The time necessary for water to pass through the drains themselves is very small compared to that required for the passage through the soil to the drain. If the spacing and depth of drains, the soil conditions and the relative elevation of the plane of saturation are the same in all parts of the underdrained area, the flow will reach all laterals at the same rate. The rate of the movement of the water through the drain is so rapid, compared with this movement through the soil, that it seems very probable that the rate of runoff will not be affected materially by the size of the underdrained area. It must be remembered however, that this statement is true only when applied to areas exactly similar in all respects except size.

The effect of topography should be studied, in each particular case, to determine its relation to an increase or decrease of the normal amount of surplus moisture and then the underdrainage designed to remove the surplus moisture at the desired rate.

Character of Soil: The relation of the properties and characteristics of soils to the rate of movement of soil moisture has already been discussed. Since the rate of runoff is but another expression of the rate of the movement of the surplus moisture through the soil, these discussions need not be repeated here. Considering each of the three physical properties of soil separately, the other two being constant

in each case, the rate of runoff varies inversely as the size of the soil grains, directly as the closeness of their arrangement and directly as the porosity.

The foregoing statements mean that a fairly fine grained soil that is loose will store a considerable quantity of moisture and will allow of its percolation at a fairly rapid rate; that a fine grained, close soil, such as clay or close "gummy" black soil, will allow of only a very slow percolation but has a large reservoir capacity, though considerable time is required for the pore spaces to become filled; that a large grained porous soil, as sandy loam, will hold but a small quantity of drainage water in storage, but allows of its percolation at a rapid rate. The relation between rainfall, including surface runoff collected on the underdrained area, the storage capacity and the rate of percolation determines the rate of underdrainage runoff.

Evaporation and the Transpiration of Plants: The amount of water which would otherwise reappear as runoff, but which is removed from the soil by these two agencies, varies with the climate, the nature and the amount of the vegetation and the character of the soil. It should be remembered, however, that unless the soil is saturated clear to the surface so that evaporation may take place directly, neither of these agencies will affect the amount of drainage water except indirectly. The relation of evaporation and the use of water by vegetable life, to the moisture content of the soil has been discussed in previous chapters which need not be repeated here. It has been estimated that, in the Upper Mississippi Valley, the average maximum daily loss from these two causes will not exceed one-tenth of an inch. However, both of these depend to a large extent on the plant growth. The water required by some plants is much more than that necessary for others. If the vegetable growth is dense and rank, the shading of the surface may be such as to reduce evaporation to a minimum.

The amount of water removed annually from the soil by evaporation and used by plants may be large in amount, but it is always small in comparison to the underdrainage runoff.

Climate and the Seasons: That the climate and the seasons have an important bearing upon the rate of runoff is readily seen from the discussions already given. In Iowa in the early spring the rainfall is ordinarily large and the losses through evaporation and transpiration are small, causing a comparatively high rate of runoff. In the summer the rainfall may be large, but these losses are also large, resulting in a lower rate of runoff. In the fall, if the amount of rainfall be large the rate of runoff will also be high, as the evaporation and transpiration losses are small. In other words, the effects of climate and seasons upon the rate of runoff are the combined effects of the resulting rainfall and the evaporation and transpiration losses.

29. **Economic Rate of Runoff:** Conditions sometimes prevail such that to provide capacities in the drains equal to the flow of surplus

moisture resulting from the maximum rate of rainfall, would require a larger investment than that upon which the average benefits from the drainage would pay an adequate return. These unusually severe storms, or series of storms, may occur at such infrequent intervals that it is economically desirable to suffer whatever loss may be due to the inadequacy of the drains during such storms than to provide the drainage system necessary at such times. The drainage systems should be designed to care for the maximum runoff for whcih it is economically possible to make provision. This rate of runoff, somewhat below the actual maximum, is often referred to as the economic rate of runoff.

In this connection it should be remembered that the more rapidly the surplus soil moisture is collected in the laterals, the higher will be the rate of runoff for which the capacities of the various lines should be calculated. Higher values for farm land and products make more efficient, more rapid, and more thorough underdrainage both desirable and possible, economically. The increasing of the general knowledge of underdrainage and its benefits are responsible for a constant tendency toward more efficient drainage. All of these things will demand that the mains and submains be designed to care for larger rates of runoff. As an underdrainage system properly constructed of good materials will last for a great many years, it will be cheaper to provide at first for a larger rate of runoff than seems necessary at that time, than to make replacements or additions within a few years when the recognized conditions demand the more efficient drainage service.

30. **Runoff Data and Values**: The designers of farm underdrainage systems have been confronted with a paucity of reliable data as to the runoffs from underdrained areas. Consequently they have had to depend upon observation of the operation of existing systems, making the capacities larger or smaller than those in some other system as the conditions appeared to demand. This condition has led to much work being designed for the care of a certain rate of runoff without really studying the particular project, or its differences from some other system. It has been the purpose of the foregoing pages of this bulletin to explain the whole subject so that the designer might make a rational study of each project, or proposed system, and then design the underdrainage system, using all available data, from publications and observations, with full knowledge of the significance of all especial conditions obtaining in the particular problem.

The data as to the rates of runoff from farm underdrainage systems given in Bulletin 52, Iowa Engineering Experiment Station, comprise practically the only published, comprehensive records for such systems. A few other data from older investigations, principally of larger county systems, are to be found, but because of their nature and the general advancement in drainage practice, these are now not

applicable without making many allowances for the advancement in drainage work.

The data in the publication just referred to show that the rate of runoff now generally used is not applicable to all cases, or, that the type of the lateral system and the completeness of the drainage have a marked effect upon the rate of flow to the drains. In fact, these data are concrete evidence of the influence of nearly all the factors discussed in the foregoing chapters.

These data show that if one rate of runoff is to be used as a basis from which to reach decision in each particular problem, this rate should be slightly larger than the rate of ¼ inch now in quite common use; in some cases this rate will need to be increased materially. The tendency is ever toward more thorough drainage, so that considerable care should be exercised to insure that the main drains of the system will have sufficient capacity for the completed and extended system of the next few years. Much of the benefit of closer lateral spacing may be counteracted by mains of too small a capacity.

The problems encountered in the design of a large county drain are capable of less exact study. The flow through the main lines of a county drain are only the combined flows from the various separate farm systems. These drains now usually are provided with inlets for admitting surface water, which add to the problem of deciding upon the probable capacity required. It is obviously impracticable and impossible for the engineer to study each individual farm and attempt to decide upon the rate of flow from the underdrainage system which the owner will install. Some landowners will install no farm drainage systems; others will construct more or less complete systems, depending upon their opinions as to the needs for underdrainage and the value of the systems to their farms. From his knowledge of the general underdrainage requirements and the local sentiment for and against thorough underdrainage, the engineer should be able to reach a fairly accurate conclusion as to the capacities to be required in the main lines of the county system. He should not forget, however, that there is a growing knowledge of underdrainage, with a resulting demand for ever increasing thoroughness of drainage. It is the moral duty of every engineer to be a constant advocate of more thorough drainage in his community. There is now no apparent reason to expect the present tendency toward better drainage to reach its climax or to turn for many years. The effect of this growth and development should not be ignored when designing any drainage system.

In designing large county drains provided with intakes for admitting surface water the engineer should increase his underdrainage rate of runoff sufficiently to care for the surface flow admitted. If this is not done the whole capacity of the drain will often be used for the surface flow and the tributary underdrains remain inoperative till this accumulated surface flow is removed.

VI. FLOW IN UNDERDRAINS.

The foregoing pages have presented a discussion of the forms of soil moisture, their movements, their relation to the various soil properties, crop production and drainage, the relationship of the rate of movement to the surplus moisture, crop requirements and soil properties to the form of the lateral system and the resulting relationship of all these to the rate of runoff, or to the capacities required in the various lines of the system. This section will take up a discussion of the factors controlling the rate of flow through the drain and the methods of computing this.

31. **Cause of Flow and Factors Affecting Rate:** The pull of gravity is the sole cause of the flow of water, except where pumps of some sort are used. It is gravity which causes water to run down hill or a ball to roll down an inclined plane.

The rate, or velocity, of the movement in the case of either the water or the ball, depends upon the steepness of the slope down which the movement takes place and the resistances which the path offers. In the case of the flow through a tile drain, the velocity depends upon the slope, or grade, of the moving water and the roughness of the inside of the drain. Obviously, the quantity of flow per unit of time is the product of the cross-sectional area of the moving column and the rate of movement.

Hydraulic Grade: In these, as in all such hydrological problems, the hydraulic slope or grade is the one which determines the velocity of the flow. The hydraulic head, when flow is due to gravity only, is the difference in elevation of the free water surface at the two extremities of the portion of the flow under consideration; the hydraulic grade is the quotient obtained by dividing the hydraulic head by the horizontal distance between the upper and lower limits of this flow.

This hydraulic grade may or may not be parallel to the grade at which the tile were laid; it will be parallel to this constructed grade only when the tile are flowing just full at both ends and neither end is submerged. However, it is customary to calculate the capacity of a drain when it is flowing full at a grade equal to that at which the tile were laid.

Resistance to Flow: The principal resistances to flow in a tile drain are the roughness of the inside of the tile, the irregularities due to careless laying, the irregularities due to tile of nonuniform shape and size and sharp or irregular changes in direction. The roughness of the inside of the tile is an inherent quality or property of the tile being used, and can be changed only by the action of the flow. The irregularities of laying cannot be entirely eliminated, but by careful workmanship this resistance can be reduced very greatly. The irregularities due to unsymmetrical or ununiform tile can be almost wholly eliminated by proper inspection of the tile before they are laid. Any channel composed of unconnected short sections, as a tile drain, will have

larger resistance to flow than a channel composed of a continuous tube of like material. The resistance due to sharp and irregular bends can be greatly reduced by making all changes in direction by means of longer, easier and regular curves; changes in the direction of the drain cannot be avoided practically, but by using proper curves this resistance is reduced to a very small amount, both actually and comparatively.

All formulas for the flow in a tile drain take into account the effect of these resistances, usually by means of a constant which varies, with the roughness of the inside of the drain, or with the size of the tile, or both. In designing a drain it is customary to consider the resistances present in a drain constructed of average good materials and in an average good, workmanship-like manner.

32. **Formulas for Flow in Underdrains:** All formulas used for calculating the velocity of the flow through a tile drain have been derived, partially at least, from the results of experiments. For this reason, all such formulas contain constants whose values must be chosen with reference to the conditions obtaining in the problem to be solved. (The constant mentioned above as expressing the effect of the resistance due to the roughness of the inside of the drain is an example.) Great care must be exercised in choosing the values of these constants in order that the values which are truly applicable be used.

Several different formulas are used, by drainage engineers in Iowa, for computing the capacities of tile drains. However, as only two of these are in general use, only these two will be discussed here. Any one wishing to study other formulas can find them stated and explained in published works on hydraulics.

Kutter's Formula: Probably the most widely used and most reliable formula for calculating the flow in tile drains is a combination of the simple basic formula proposed by Chezy and the more complex formula proposed by Kutter and Ganguilet for determining the value of the constant in the Chezy Formula. This combination is usually spoken of simply as Kutter's formula. Some new formulas for the flow in circular channels have been derived and found to be more satisfactory than Kutter's formula for the particular cases studied. As yet no new formulas especially adapted to the calculation of flows in tile drains have been published. Kutter's formula is probably accepted as the most accurate one available in a very great majority of such hydraulic problems.

Chezy's Formula is:

$$V = C\sqrt{r\,s}$$

where V=the velocity in feet per second,
C=a constant, depending primarily, on the resistance to flow from different causes,
r=the mean hydraulic radius,
s=the hydraulic slope or grade.

The constant in this formula was determined by Kutter and Ganguilet to be:

$$C = \frac{41.6 + \frac{.00281}{s} + \frac{1.811}{n}}{1 + \frac{\left(41.6 + \frac{.00281}{s}\right) n}{\sqrt{r}}}$$

where s=the hydraulic slope,
n=the coefficient of roughness,
r=the mean hydraulic radius.

The mean hydraulic radius, r, is determined by dividing the area of the cross-section of the flow by the area of the wet perimeter per unit length of channel. In circular pipes flowing full, r equals one-fourth the internal diameter.

The value of the "coefficient of roughness," n, varies from .010 for very smooth continuous pipe to .020, or even more, for poorly constructed drains. The best available information and the best drainage practice favors the use of a value of .015 for the coefficient of roughness of average good tile drains.

In Table XI is given summary of the results obtained in an investigation of the value of "n" for several Iowa drains. These data were collected in 1909 by Messrs. Rightmire and Chappel as a thesis, the work being done under the direction of the Iowa Engineering Experiment Station. The data given below are taken from the complete report of these investigations given in the Engineering Experiment Station Bulletin, Vol. IV, No. IV.

In these investigations the discharge from the drain being investigated was measured by means of a weir. The hydraulic slope and depth of flow were determined for five consecutive stations of about equal length. With these data the value of "n" for each station was computed, and the average of these taken as the value for the drain.

TABLE XI.

THE COEFFICIENT OF ROUGHNESS IN AVERAGE IOWA DRAINS.

Size	Material	"n"	Character of Grade	Depth of Flow
2′x32″	Cement	.01504	Irregular	23½″ to 24 1-3″
2′x24″	Cement	.01638	.01% to .09%, irreg.	½″ to 2¾″
2′x20″	Cement	.01146	Regular	7¾″ to 9½″
2′x18″	Clay, hard burned	.01172	.3% to .6%, regular	4″ to 7½″
2′x14″	Clay, hard burned	.01525	1% to 2%, irreg.	1½″ to 3″
1′x12″	Clay, hard burned	.01683	.15% to 1.1%, irreg.	1¼″ to 2½″
1′x10″	Clay	.0164	1.2% to 1.7%, fairly irregular	½″ to 1″

These data are too few to be conclusive, but they seem to bear out the use of the value of .015 for "n" with well laid Iowa drains. It is

quite certain that this value of "n" is too large for some very carefully constructed drains, but in such cases the error is not large and is on the side of safety. As far as is shown by the above data, the or' · variation of "n" is with the regularity of the grade and possibly n the length of the individual tile, as the number of joints is in-·. ased with shorter tile.

Use of Kutter's Formula: In actual use of this formula the value of the constant "C" is not computed, but is taken from either a diagram or from tables. Having the value of "C" the velocity is easily computed, or taken from a table, and from it the discharge determined. Tables and Diagrams giving the values of "C" for different slopes and depths of flow are given in many texts and handbooks, so are not repeated here. Trautwine's "Civil Engineer's Pocket Book" gives very complete data of this kind.

Another method of simplifying the use of this formula is by means of diagrams, or curves, which show the discharges for various sizes of drains at various slopes. These diagrams can be prepared for any shaped channel with any depth of flow at any slope, and for any degree of roughness as indicated by the coefficient "n." Such a diagram for tile drains from 4 inches to 48 inches in diameter flowing full at hydraulic grades of from 0.02 feet to 5.0 feet per 100 feet, when "n" equals .015, is given as Fig. 8. At the right of the diagram has been added a scale showing the number of acres drained, at different rates of runoff, for different discharges in cubic feet per second. This diagram is as accurate as is possible considering the probable errors of plotting and reading the curves. Any engineer desiring to use such a diagram in his work should prepare one to a larger scale on mounted paper which is not subject to great change under different temperature and humidity conditions.

In preparing these diagrams it is preferable to plot them to a logarithmic scale, as this gives a straight line for the discharge for each size of tile. In this way the diagram may be prepared by plotting the discharge for each size of tile at three grades and then connecting these points with straight lines. The scales at the right of the diagram are prepared simply by platting the number of acres drained at different rates of runoff opposite the equivalent discharge in cubic feet per second.

This use of the diagram may be explained by two examples:

1. What is the discharge from a 15 inch drain at a grade of 0.20% or 0.20 feet per 100 feet? Follow up the vertical line from the notation 0.20 at the bottom of the diagram till this line intersects the discharge line for 15 inch tile and then across horizontally to the scale at the left, where the result is found to be approximately 2.28 cubic feet per second.

2. What size of tile, laid at a .015% grade, will be required to drain 500 acres at a ⅜-inch runoff? Follow up the vertical line representing a grade of .015% till this intersects the horizontal line from

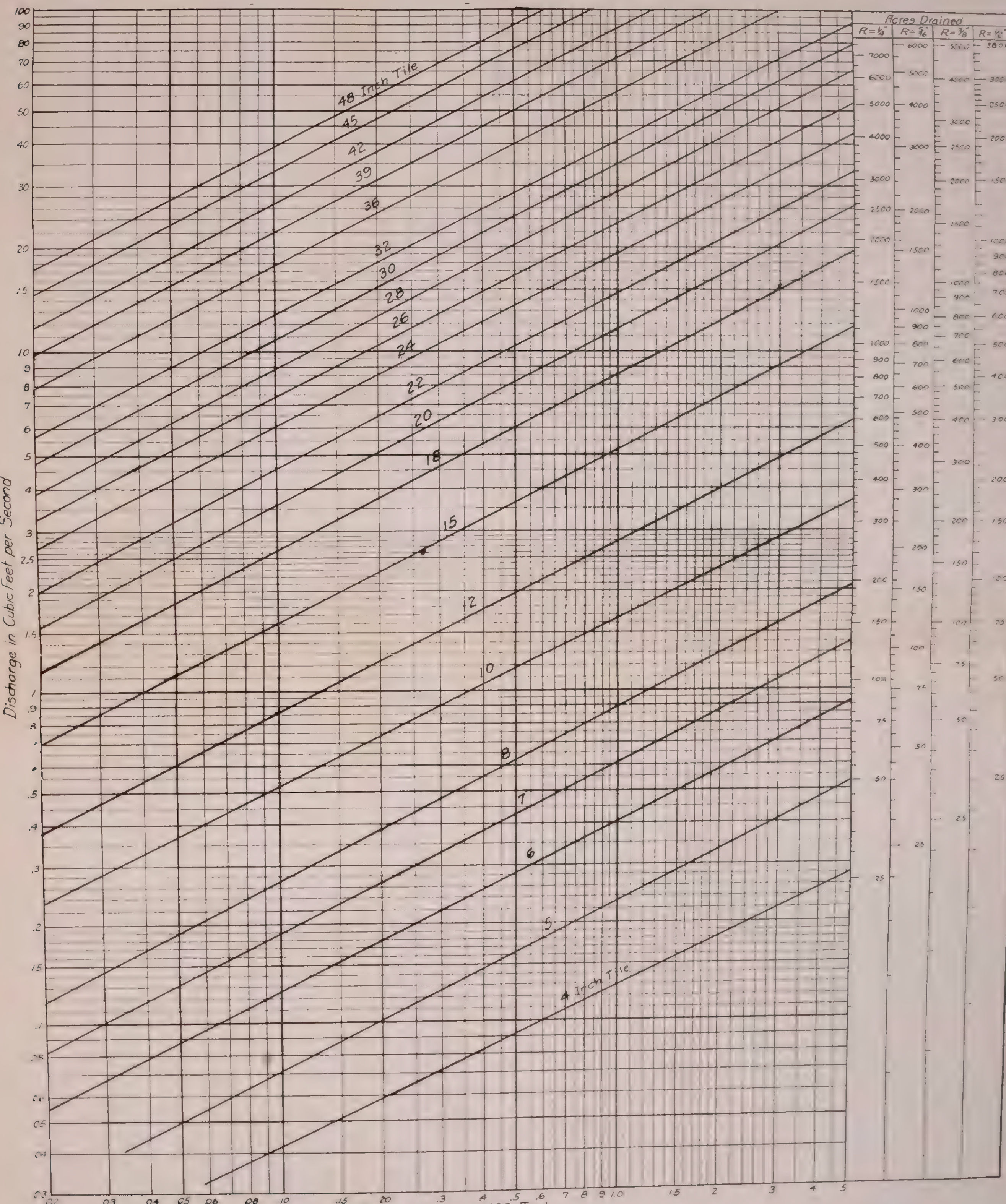

Fig. 8. Capacities of Drains as Given by Kutter's formula with "n"=.015.

500 acres at a ⅜-inch runoff on the scale at the right. This intersection shows that a 24 inch tile is slightly too small and a 26 inch tile too large. The engineer must use his judgment in deciding between these two sizes, though in a case of this kind, it is often better to have drains too large rather than too small. In designing a drainage system all drains should be designed to have the required capacity when the hydraulic grade is parallel to the constructed grade, or when flowing full but under no head other than that afforded by the slope of the drain. If this is done, the drain will have extra capacity for the flow from unusual storms and spring freshets when the water will be backed up at the upper end of the drain causing a steeper hydraulic slope. Another reason for not designing the drain to work under extra head is that the pressure will often cause water to pass out through cracked tile and wash or soften the earth so as to allow these cracked tile to spread and collapse.

Poncelet's Formula and Elliott's Modifications: The other formula, or rather a set of formulas, in general use among Iowa drainage engineers is termed, very often incorrectly, Elliott's formula. This set of four formulas proposed by Mr. C. G. Elliott, formerly chief of Drainage Investigations, U. S. Department of Agriculture, consists of Poncelet's formula and three modifications suggested by Mr. Elliott.

Poncelet's Formula:

$$v = 48 \sqrt{\frac{d\,h}{1 + 54\,d}} \quad \text{and } Q = av$$

where v=the velocity in feet per second,

d = the inside diameter of the tile in feet,

h = the head, or difference in elevation between the outlet and the upper end, in feet,

l=length of the drain considered, in feet,

a = the area of the cross-section of the flow in square feet,

Q=the flow in cubic feet per second.

In order to give consideration to some other factors Mr. Elliott suggested three modifications of Poncelet's formula, each of the four to be used under certain conditions. He first introduced a factor "k," or fractional part of "k." This factor represents the depth of earth over the upper end of the drain. If the soil is loose and becomes saturated the water therein was taken as creating an additional "head" which would increase the flow through the drain. In loose soil he recommended that "dh" be increased by ½ "k."

Another factor which he considered as increasing the capacity of the drain is the increase in velocity which may be caused by the number and grades of the submains. In order to take this into account further modification is suggested by replacing "h" by "the quantity."

$$h + \frac{b}{n}$$

in which h = the head, in Poncelet's formula,
b = the sum of the amounts of the excess head in the submains,
n = the number of submains.

The amount of excess head in each submain is the difference between the head on it and that for a like length of the main.

Mr. Elliott recommends the uses of these four formulas as follows:

Poncelet's formula:

$$v = 48 \sqrt{\frac{dh}{1+54d}}$$ for use in small systems in close soil and, as a general rule, for outlet mains.

Elliott's modifications:

$$v = 48 \sqrt{\frac{dh + \frac{1}{2}k}{1+54d}}$$ for use in systems where soil is open.

$$v = 48 \sqrt{\frac{d(h + \frac{b}{n})}{1 + 54d}}$$ for use in large systems in close soil.

and $$v = 48 \sqrt{\frac{d(h + \frac{b}{n}) + \frac{1}{2}k}{1+54d}}$$ for use in large systems in open soil.

Trawtwine's "Engineer's Pocket Book" recommends that for pipes larger than 12 inches in diameter the following numbers be used instead of the constant 48:

For 18	inch	pipe,	coefficient,	53
24	"	"	"	57
30	"	"	"	60
36	"	"	"	62
42	"	"	"	64
48	"	"	"	66
60	"	"	"	68

Use of "Elliott's" Formula: The use of either of these formulas may be simplified by the preparation of tables or diagrams showing the

discharge in cubic feet per second, or the acres served at a given rate of runoff, by various sizes of drains at different grades. A separate discharge table must be prepared for each formula. A separate "acres-drained" table must be prepared for each formula and each rate of runoff used.

The general discussions as to the use of Kutter's formula apply equally when either of these formulas is used.

33. **Advantages of Each of the Two Formulas:** Hydrologists quite generally consider Kutter's formula more accurate than Poncelet's for calculating the flow through pipes. Authorities on sewer design generally consider that the flow through a sewer is given more accurately by Kutter's formula than by Poncelet's; practically all texts on sewer design recommend the use of either Kutter's formula, with a value of .015 for "n" for pipe sewers, or of some form of exponential formula which has been especially adapted to sewer design.

The accuracy of Elliott's modifications of Poncelet's formula is often questioned on the ground that they are based on unsound premises. It is probably true that under certain extreme conditions, the soil above the drain may become so saturated that the water in this soil would tend to increase the head on the drain. This condition would not obtain, however, if the drains had the capacity to remove the water as rapidly as it passed through the soil to them. No water which is flowing has any actual head upon it unless the drain is surcharged; up to the capacity of the drain, all static head is converted into velocity head or used in overcoming frictional resistance. In other words, it would seem that the premise on which Elliott's first modification is based could be true only when the water is moving through the soil to the drain more rapidly than it can flow away through the drain.

Elliott's second modification is made to care for an increase in velocity due to the fact that the submains have a steeper grade than the main. This case is very similar to that just discussed except that, when the velocity in the submain is greater than through the main, this excess in velocity is converted into static head when the flow passes into the main. The extra head so created would, however, be small, and it is difficult to see how the velocity in the main will be increased materially by that of the submains so long as the main has sufficient capacity to care for all the flow entering it without backing water up in the submains.

The use of tables and diagrams makes these two formulas (Kutter's and Poncelet's) equally easy to use. Familiarity with the tables or diagrams of either enables the engineer to use either speedily and accurately. It is obvious that if the capacities are to be determined by solving the complete formula in each calculation, either of Elliott's formulas can be used with much less tedious labor than Kutter's.

For small tile Elliott's basic formula (Poncelet's) gives larger capacities than Kutter's; the difference in the results by the two

formulas decreases as the size of tile increases so that for 20 inch or 24 inch tile they give very approximately the same result; for the larger sizes there is little difference, comparatively, though Kutter's formula gives the slightly larger capacities. The fact that Elliott's formulas allow the use of smaller sizes of tile, within the range of sizes common to farm tile systems, than Kutter's is an argument against them as the sizes used in such systems are too small much more often than they are too large.

VII. RESULTS OF UNDERDRAINAGE.

The results, or effects, of underdrainage may be divided into the three classes; financial, physical and general. However, any such classification must be quite elastic, as the financial and general results are due either directly or indirectly, to the physical changes brought about by the construction and operation of the underdrainage system. On the other hand, the resulting financial gain or loss is usually the most apparent result of the prosecution of the drainage work.

34. **Financial Results**: The financial returns from any drainage improvement work will usually be taken as a measure of the success of the work. Probably the only exception to this is found in the comparatively rare cases where the drainage is resorted to as a means of protecting the health of the community and for no other purpose. Even in such cases, the probable value of the reclaimed land is usually given serious consideration before the work is started.

When a drainage improvement is proposed the owner of each parcel of land to be affected by the proposed drain will ask himself the question, "How and to what extent will this drain benefit me?" The direct results of the construction of the drainage system will be changes in the physical condition of the lands drained. Certain of these physical changes will afford the landowner a financial gain.

The removal of the surplus water from a piece of wet land will change this tract from an unproductive to a productive area. By reason of this change the actual sale value of this land will be increased in proportion to its increase in productiveness.

This increased productiveness will make possible a direct financial gain in the greater value of the crops raised. Proper drainage will make the cultivation less difficult, thus making the cost of producing the large crop less than that of raising the small crop.

Another, though smaller, financial gain from proper drainage results from the lessened cost of transporting the farm produce to a market or shipping point. It is a well proven fact that good and economical highway construction must be preceded by drainage. The removal of the surface water by open ditches is no more important in this respect than the removal of the surplus ground water so as to provide a firm foundation for the roadway. The cost of hauling the farm crops over a good highway is much less than that of hauling

this same crop over a poorly constructed and poorly maintained road.

If improper drainage works are constructed, the financial results will be smaller or may even constitute a loss. If the conditions are not improved by the construction of the drain or drains, the cost of the work and the loss of the benefits which would have resulted had the work been properly designed and constructed will constitute no small loss.

35. **Physical Results:** The direct effects of underdrainage are the physical changes which are due to the operation of the drains. The most important of these physical changes are those which take place within the soil, the character and mechanical composition of an over-wet or water logged soil being completely changed by underdrainage. It is significant that all the physical changes resulting from underdrainage are classed as benefits by agriculturists and that many of these are due wholly or in part to actions which take place when the surplus soil moisture is removed.

The following short discussion of the effects of underdrainage is but a recapitulation and application of the discussions given in the earlier sections of this bulletin.

1. *Improves the Physical Character or Mechanical Composition of the Soil:* Underdrainage aids greatly in the formation of soil granules. The granular structure is particularly desirable in fine grained soils, as they then have the desirable properties of coarser grained soil in permitting of the rapid passage of moisture and air. One of the important factors in soil granulation is alternate wetting and drying.

When a soil is saturated the soil grains are held apart, and partially floated, by the water. In addition to this, the water acts as a lubricant so that the soil will not support the weights necessary in cultivation. When the soil is saturated continually the soil granules are broken down and the smaller grains move into the spaces between the larger ones. In this condition the soil becomes almost a compact mass and is termed puddled. Underdrainage prevents puddling.

These actions and conditions are often expressed by saying that underdrainage makes the soil more loose, more open or more mellow, and that standing water, or saturation, packs it. These are but different methods of expressing the conditions discussed above.

2. *Improves the Aeration:* Many agriculturists hold that the physical changes which cause a more rapid and greater passage of air through the soil is the largest single benefit of underdrainage in that thorough aeration is one of the most important factors in crop production, in so far as this depends upon the condition of the soil. Underdrainage improves the aeration in two ways; it removes the surplus, or gravitational moisture, thus leaving the soil pores open for the passage of air; and promotes soil granulation, thus providing larger channels for the circulation of air.

3. *Increases the Supply of Available Plant Food and Moisture:* This is probably the most important effect of underdrainage upon the soil, but it was not taken up till now because of its dependence upon (1) and (2). This effect is due to several actions, all resulting from the drainage, the most important of which will be mentioned.

It has been explained that plant roots take up food that is in solution in soil moisture; that they can take up this moisture only when it occurs in the soil as capillary moisture; and that the capillary moisture is present only after the surplus, or gravitational, moisture has been removed. This chain of facts makes it at once apparent how underdrainage may increase the available supply of plant food. Underdrainage lowers the plane of saturation, thus making available the food supply of a larger volume of soil.

By causing the formation of granules, the underdrainage increases the amount of capillary moisture and thus increases the food supply.

Underdrainage improves aeration which in turn causes the formation of additional plant food in the soil.

Underdrainage promotes the growth of the desirable forms of soil organisms and retards the growth of the undesirable forms. If the soil is saturated, the products of these organisms are held in the soil causing the destruction of all organisms. These desirable organisms increase the amount of plant food in the soil.

Underdrainage increases the supply of plant food through chemical changes which are dependent upon this moisture condition.

It has already been explained that underdrainage causes certain changes in the physical character of the soil and thus increases the maximum content of available or capillary moisture. This explains why crops in a thoroughly drained field withstand drouth better than those in a similar undrained field. Underdrainage increases the supply of available plant moisture by removing the injurious surplus gravitational moisture from a wet soil and by causing physical changes in the soil that result in the storage of an increased supply of available moisture in the soil after this surplus has been removed.

The benefits of underdrainage in increasing the supply of plant food and moisture are well illustrated by Fig. 9. The measurements from which this diagram was prepared were taken at the foot of a slope where possibly seep water was present. It will be noticed that the stalks of corn grew much stronger directly over the lines of tile where the drainage was most thorough.

4. *Raises the Average Temperature:* The specific heat of water is much higher than that of soil. The greater the proportion of water a soil contains the more heat is required to raise the temperature of the sample a given amount. The continual evaporation from the surface of a wet soil reduces the temperature or retards the increase in temperature. The heat applied to a given soil area is fairly constant, so that if this heat must be used up in evaporating water the temperature of the soil body is not raised.

Drainage removes the excess water from the soil, reducing the heat required for evaporation and causing the soil body to warm up more readily. As a result of this, a drained soil warms up much earlier in the spring, and so lengthens the growing season. This enables the farmer to start his spring work earlier, which is especially valuable

Fig. 9. Diagram Showing the Effects of Drainage Upon the Height of Corn at Hanford, Cerro Gordo County, Iowa, October, 1910.

in a so-called "backward" spring. The growth of the crop upon drained land is greatly benefited by the high temperature that prevails here in the spring and fall. Investigators have found that at a depth of seven or eight inches a drained soil is from 12° to 15° warmer than an undrained soil of the same nature and in the same climate.

5. *Reduces Heaving:* It is often noted that posts have been raised out of the ground during the winter. This heaving is due to the freezing of a wet soil. When water freezes it expands one-eleventh of its volume and in a saturated soil this expansion must be upward, the amount of the heaving depending upon the amount of water in the soil and the depth to which it is frozen. This same action tends to raise the roots of certain crops out of the ground, as the soil settles back after thawing, more rapidly than the plant root. This heaving also breaks many of the small roots.

6. *Reduces Erosion:* In an undrained area all of the rainfall must either be absorbed by the soil or pass away over the surface. In a continued rainy season the soil soon becomes saturated after which all the rainfall must flow away over the surface. The particles of the saturated soil are easily displaced and carried away by the water.

In an underdrained area the soil has a greater water capacity and allows of a continual removal of the surplus water by the drains. This greatly reduces the amount of water which must pass away over the surface and thus reduces erosion. Underdrainage of slopes will often prove a profitable investment if installed for no purpose other than reducing or preventing erosion.

36. **General Results:** Those results of the physical changes brought about by drainage, to which cannot be readily assigned a

monetary value, are termed general benefits. In the well drained section the better highways allow of more, easier, and more rapid travel. The benefits of this in a social way are no small matter. The rural mail service demands better highways than are usually possible without both open channels and underdrainage in many sections. The consolidated school depends upon the possibility of transporting the children to and from school, and this in turn depends upon good roads. The appearances and generally better financial condition in the well drained territory add to the value of the farm. The sanitary condition in wet or swamp areas are bettered materially by both open ditches and underdrainage.

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